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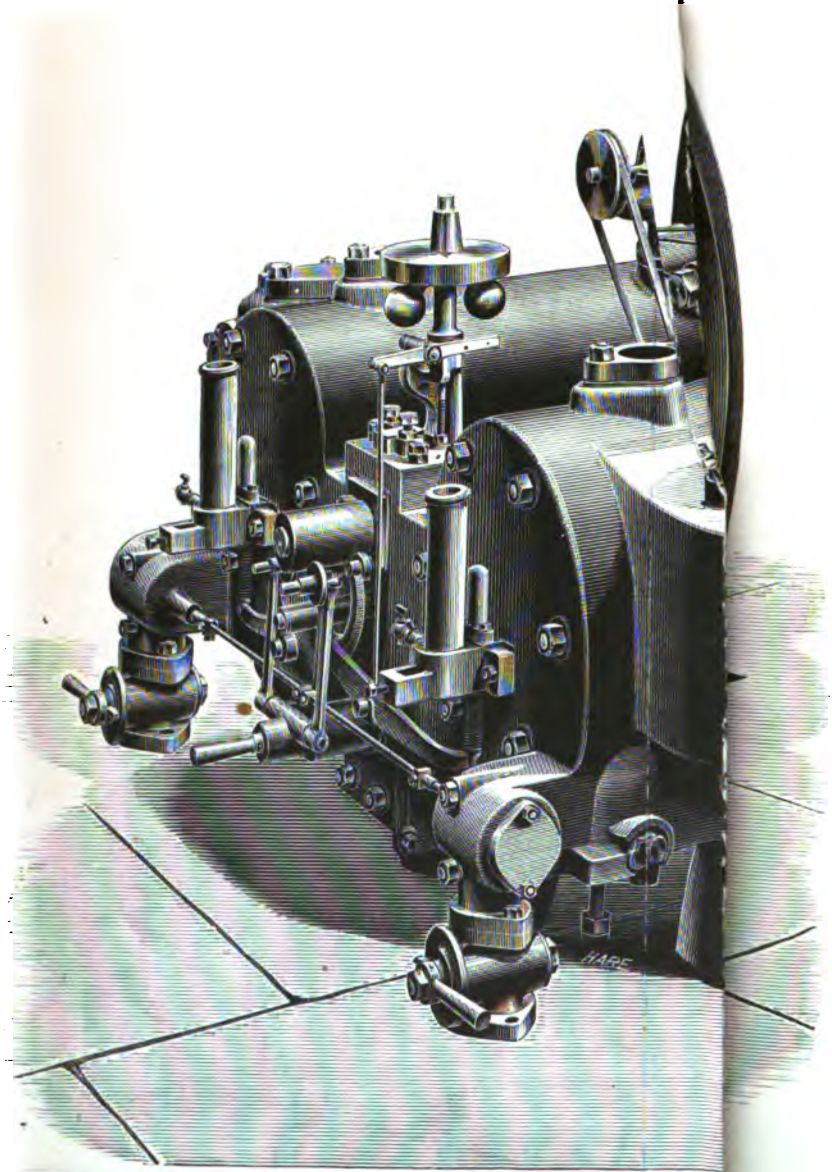

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**Finsbury Technical Manuals.**

# GAS AND PETROLEUM ENGINES:

## A PRACTICAL TREATISE ON

# THE INTERNAL COMBUSTION ENGINE.

BY

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WITH NUMEROUS ILLUSTRATIONS.

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# PREFACE.

THIS book is intended to aid students and practical men in studying Gas and Petroleum Engines, and the principles that underlie and control their action, so as to put the practical man in a position to test the performance of these engines, and to make an intelligent use of his own experience and observations. Several years' experience in the teaching of technical students and practical workmen has led me to bring out this work, which I have endeavoured to make complete in itself as a text-book on the subject.

15 8 '31

The general term *Internal Combustion Engine* is here applied to the various forms of heat-engine in which the working fluid—by combustion in the motor cylinder—generates the heat necessary to cause its own expansion, and to do actual work.

The most common type of gas engine is first described, and then those modifications of it which use cheap gaseous fuel and petroleum oil.

Brief historical notes of early inventions are given, showing the evolution of the Internal Combustion Engine, from the crude and dangerous Powder Machine to the Modern Gas Engine, which has established itself as a useful, safe, and handy prime-motor.

It has, of course, been impossible to enumerate, much less describe, all the gas engines in the market. I have, however, dealt with the common representatives of the various types most used in practice, and those which are not mentioned can be easily understood thereby.

Special attention has been given to what, from the practical standpoint, is most important, namely, the consumption of fuel, and the utilisation of the waste heat, keeping before the student the lines along which experience shows improvement may be expected.

The mechanical details of each engine have been taken up in connection with the description of its action, although the student can only obtain complete information on this subject by carefully examining engines himself, sketching, and making working drawings of their various parts.

The account of elementary principles is intended to give exact notions, without which it is impossible for the student to make quantitative experiments, measurements, and calculations on Heat and Work. With this end in view, indicators and the other necessary measuring instruments are described, and their use explained. Moreover, I have not scrupled to work out practical numerical examples in the text, the reader being expected to know decimals, the ordinary rules of arithmetic, as well as the meaning and use of simple algebraic symbols.

Again, no elementary text-book is found to take up, in a concise and practical manner, the subject of gaseous fuels and the modern appliances devised to produce them directly from coals, oils, fats, and substances capable of yielding combustible gases. Elaborate and expensive treatises on the subject of fuel are not always within reach of practical men, and the most useful and modern information is usually wrapped up in the Proceedings of the various Scientific Societies. Hence I have given a short account of the production, composition, and heat-value of the different kinds of fuel—solid, liquid, and gaseous—used with the Internal Combustion Engine up to the present date.

The laws of gases are briefly dealt with, as introductory to the fuller consideration of the behaviour of the working fluid in the engine cylinder. The performance of the actual engine is then compared with that of the hypothetical engine of its type, and the causes that lower the efficiency are pointed out. The reader who cannot follow the more thorough mathematical treatment requisite to a complete understanding of the application of the principles involved, may nevertheless avail himself in many ways of the rules arrived at. Thus, from the laws of expansion and compression already deduced graphically from indicator diagrams, he can solve numerical problems on the work done in the engine cylinder during the various operations.

The last chapter is devoted to the necessary tests and measurements for the efficiency and regularity of working of gas engines, whilst the results of some public trials are appended as examples.

My thanks are due to the Council of the Institution of Civil Engineers and to the Council of the Society of Arts, for their courtesy in allowing me to use their blocks for the illustration of some of the machines used and the diagrams obtained in these trials. It also affords me much pleasure to acknowledge my indebtedness to numerous friends and firms for their kindness and readiness in supplying me with particulars, as well as with many blocks for the purpose of illustration.

For the method adopted in treating some parts of the subject I am greatly indebted to Professor John Perry, M.E., D.Sc., F.R.S., whose lectures on gas engines, before any text-book was available on the subject, form the basis and origin of this book. My cordial thanks are also due to Professor Silvanus P. Thompson, D.Sc., B.A., for many suggestions in the preparation of the work and much useful information derived from intercourse with him as Principal of the Technical College, Finsbury. I also desire to thank other friends in this college, both colleagues and students, who have given me assistance and looked over some of the proofs.

WILLIAM ROBINSON.

CITY AND GUILDS TECHNICAL COLLEGE,
FINSBURY, LONDON.
*March* 1890.

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# GAS AND PETROLEUM ENGINES.

## CHAPTER I.

## INTRODUCTORY.

A MACHINE which converts heat energy into mechanical energy is called a *heat engine*. The best known heat engine is that in which steam is the working agent; many other engines in which hot air is the working agent are known to the student rather than the engineer, but particular forms of the combustion engine, which are usually called *Gas and Petroleum Engines*, are coming more and more into common use.

In the history of civilization there is no invention which can compare in its effects with THE STEAM ENGINE. Since the time of Watt the attention of mechanical engineers has been chiefly directed to the various applications of the steam engine and to improvements in the details of its mechanism. Becoming more familiar with its action, engineers have made it a very useful servant to perform all sorts of work for them, and Stephenson caused the horses of the old Stage Coach to give place to the locomotive engine. Even now, towards the close of the nineteenth century, when England is covered with a network of railways which leave no important village in the whole country without its railway station, many of our readers can, doubtless from their own experience, contrast the luxuries of cheap railway travelling with the laborious and tedious stage-coach locomotion; and although it would hardly be possible now, even in the most unfrequented part of the Pacific Ocean, for a small boat with a starving crew to remain for more than two days without the sight of a steamer's smoke appearing at least once on the horizon, the head of the firm who first carried out the idea of having a line of steamers across the Atlantic is still alive. It is quite useless to dilate on the fact, that since steam has given to the master of a vessel the power of propelling his ship without a fair wind and against opposing winds, commerce and industry have been stimulated, and the natural resources of the whole world have been developed.

Still, when we bring the steam engine to account, and compare carefully its consumption of fuel with the work done by it, we find that there is enormous waste. Thus a consumption of 1½ lb. of coal per hour per horse-power is regarded as an exceedingly good performance in a steam engine, yet it means a utilisation of only about 12 per cent. of the total quantity of heat generated by the burning of coal; and with 6 lb. of coal per hour per horse-power (which is not uncommonly thought to be economical in London) there is only a utilisation of about 3 per cent. of the total heat energy.

In 1885 thc Corporation of Birmingham had tests made on six non-condensing steam engines, taken indiscriminately from among users of power, and ranging from 5 horse-power to 30 horse-power nominal, and found that the consumption in one instance was as high as 27·5 lb., while it never fell below 9·6 lb., and the average of the whole was 18·1 lb. per hour per indicated horse-power. Other tests of a large number of steam engines under 20 horse-power give an average of 11 lb. of coal per hour per indicated horse-power.

It is true that in Shakespeare's time the poet could speak of a sea-coal fire, but the coal resources of England cannot be said to have been appreciated earlier than by our grandfathers, and at the present rate of consumption our grandchildren will see the end of our accumulated stores of energy in this form. The spendthrift talks of the new fortune that will come to him, anyhow, somehow, when his present fortune is spent; and it is customary for pseudo-scientific people to talk of some store of energy in another form than that of coal which will make its appearance in the world when our present store is spent; but we confess that, with a knowledge that 96 or 97 per cent. of the energy stored up for us is now being utterly thrown away by the people who burn coal in steam engines of small power, showing as it does that we are unworthy of the benefits vouchsafed to us, we feel that we are simply spendthrifts placing a vague dependance on the appearance of a new fortune when our present one is dissipated.

Now the best steam engines are very nearly as economical as any heat engine can be with the limits of temperature at which they receive and reject the steam. In design and construction there is no great room for improvement. As an engine the steam engine is nearly perfect, but so much the worse for the steam engine. Its possibilities are limited by the fact that in any heat engine the amount of heat transformed into mechanical power depends on the limits of temperature between which the engine works. We prefer to leave out of consideration the ordinary non-condensing engine, which is such that even if it receive steam at a pressure of eight atmospheres from a boiler and reject it at a pressure of one atmosphere, it receives the steam with 915,000 foot-pounds of energy in every pound, and rejects it with 885,000, so that, however economical the mechanism may be, the engine can only utilise one-thirtieth of the energy which is received, whereas in a perfect heat engine, it can be proved that within the same limits of temperature, nearly one-sixth of the total energy received might be converted into mechanical work. Modern condensing and triple-expansion steam engines are, however, very good forms of heat engine; still, in them, as in other forms of heat engine, the greater the range of temperature (other things being equal) the more heat is utilised. But steam cannot be employed at very high temperatures, first, because of its burning action on the lubricant employed for the piston, and second, because of the inconveniently high pressures which would be required in the boiler and pipes leading to the cylinder.

It is, therefore, not possible for the steam engine to convert much of the heat of combustion of the fuel into mechanical energy, and some other prime motor less wasteful is needed; but until very recently the ingenuity of inventors was almost exclusively exerted on details in the steam engine, so that for large amounts of power its use is not yet superseded.

In spite, then, of the great amount of thought which has been given to the steam engine, we think it absolutely necessary that engineers should turn their attention to the use of some working agent other than steam in heat engines; and as the *gas* engine has already achieved promising results, we will first consider it as the modern representative of hot-air engines.

In the GAS ENGINE the working agent is a mixture of gas and air, which generates heat by its own combustion within the working cylinder. In the other forms of heat engine the steam and air receive heat from an outside source, and then do work by expanding between two given temperatures, whereas in the gas engine the energy to be transformed is contained in the working fluid itself. The gas engine is, in fact, an INTERNAL COMBUSTION ENGINE, the working cylinder being the furnace. Hence very high temperatures can be easily obtained. The outside of the cylinder is usually kept at a low temperature by cold water circulating round it. This water runs away with a large proportion of the total heat generated. Some means may be devised by which this waste heat can be utilised, or at least greatly reduced. Notwithstanding this great loss, it is found in practice that even small gas engines actually convert into useful work more than 20 per cent. of the total heat of combustion, and are thus less wasteful of fuel than the largest and most carefully constructed steam engines.

A great convenience of the gas engine consists in its being always ready for use at a moment's notice. It is started by simply turning on the gas, lighting the gas jet, and giving the fly-wheel a turn or two. Some engines are provided with automatic self-starting arrangements. It is thus specially adapted for intermittent work. There being no boiler, it does away with the risk and danger of explosion, as well as the tedious process of getting up steam. When kept properly cleaned the gas engine requires little or no attendance, and does not make the room in which it works uncomfortable with heat or dust. Moreover, the space required is small, as is also the first cost, attendance, and maintenance.

These important advantages render the gas engine very desirable as a prime motor. Of late years it has come extensively into use, and has found numerous applications for various industrial purposes, and there is a large and increasing demand for this class of motor. As yet this type of internal combustion engine is only in its infancy, and there is great room for improvement, considering the very high temperatures that can be utilised. It is gradually becoming clearer to engineers and others, that even small specimens of this kind of engine are more economical of fuel than the steam engine. It is therefore not unreasonable to suppose that in the future development and application of the internal combustion engine we may expect to see it entirely supplant the steam engine for small powers. The high price of ordinary lighting gas makes the *unit of heat* from gas more expensive than that from coal; hence for large powers the internal combustion engine, using ordinary coal gas, cannot compete with the large steam engine using coal.

A CHEAP FUEL-GAS specially adapted for gas engines has been introduced by Mr. J. Emerson Dowson. This gas has been largely used for driving Otto engines, and the economical results obtained with this combination are interesting and important, the gas apparatus and gas engine being closely analogous to the boiler and steam engine. In ordinary working it is found that with a Dowson gas plant, not larger than the boiler used in the corresponding size of steam engine, an Otto engine uses only 1·3 lb. of coal per indicated horse-power per hour.

With a small engine developing no more than 4·4 indicated horse-power, Mr. D. K. Clark, M. Inst. C.E., found that the total fuel consumption was only 1·4 lb. per indicated horse-power per hour. For years past Messrs. Crossley Brothers, the English makers of the Otto engine, have driven all the engines at their works with Dowson gas, instead of steam power, the aggregate being about 200 horse-power. After a trial lasting 35 weeks, they found that the total fuel consumed was barely 1·3 lb. per indicated horse-power per hour, during the whole of that time. At these works gas is only made in the day-time, and the fuel consumption includes the waste during 244 nights and 34 Sundays. One man makes all the gas required, and in addition he has charge of two engines, and does other odd jobs.

Careful tests with an Otto engine indicating about 32 horse-power have shown that the total fuel consumption, including that used for the production of superheated steam and getting up the fires at starting the Dowson generator, was only 1·2 lb. per indicated horse-power per hour. In this test the gas was made from garnant anthracite, but in another trial with water-gas made from ordinary gas-coke costing 5*s.* 6*d.* per ton, the total consumption was at the rate of 1·4 lb. of coke per indicated horse-power per hour. This economy is never realised with the best type of steam engine and boiler of the same power.

Other forms of gas engine, when worked with cheap fuel gas such as Dowson gas, promise still more favourable results.

Independent of coal altogether, we have modern representatives of the steam boiler in the numerous modern PRODUCERS OF GAS from cheap oil. As an example, we select the MANSFIELD OIL-GAS APPARATUS, which needs no skilled labour, and produces gas, using oil of any kind—mineral, vegetable, or animal; *native* oils, as the crude petroleum and rangoon, in America, Russia, Egypt, Australia, China, etc.; the *cocoa-nut* and *palm oils* in Africa; mutton *fat* and *tallow* in Australia and South America; various kinds of fatty refuse in Jerusalem; and intermediate oils in the United Kingdom. Attached to the producer is the simplest kind of gas holder and tank, which stores the gas for use in the engine. This arrangement can be used in the most remote country districts all over the civilised world, being equally available to the American backwoodsman and the Australian squatter.

The COMMON PETROLEUM ENGINE is the most recent, and in many respects a most useful development of the combustion engine. Ordinary petroleum oil can be obtained in abundance almost everywhere, even in the most inaccessible localities. In such places, a prime motor which uses only this oil, at once as fuel and working agent, supplies a much-felt want.

The Priestman Petroleum Oil Engine *directly* employs the common petroleum oils, including the heavy Scotch paraffin with a specific gravity of ·820 and flashing point of about 150° F., and can also work satisfactorily even with the common creosote oil. Ordinary heavy lamp oil of specific gravity above ·800, and flashing point 100° F. and upwards, becomes in this engine a safe and economic source of power. Repeated tests show that the consumption of oil in this engine is about 1·1 pint per actual horse-power per hour with full load. Mineral oil has frequently been purchased, even in England, at 5*d.* per gallon, costing less than 1*d.* per actual horse-power per hour. Common creosote can be used at 3*d.* per gallon, costing about one halfpenny per actual horse-power per hour. In many countries this rate of consumption of ordinary petroleum oil would cost only a very small amount compared with coal. The present cost of power from oil is sure to be reduced by future improvements. In addition, it is worthy of note that the engine is completely self-contained, of simple construction, and requires little or no attention when running.

There are, in fact, three parts which petroleum, or other volatile liquid hydrocarbon, may play in prime motors :—

1. *Fuel* merely as a substitute for coal, where the latter is expensive and oil plentiful.

2. *Working agent* in the cylinder when converted by heat from the liquid to the gaseous state, in the same way

that power is obtained in the steam engine from water converted into steam.

3. *Both fuel and working agent* for the internal combustion engine, the heat generated by the combustion of the oil being used directly to expand the products of combustion and so drive the piston.

The first and second of these uses of petroleum we shall only deal with briefly and incidentally, whilst treating the third more fully, as that with which we are chiefly concerned.

The rapid growth of this new application of science renders it necessary that help should be given to practical men to enable them to use such observations as they are constantly making. We intend, therefore, in the following chapters to consider the **internal combustion engine,** with the principles that underlie and control its action.

# CHAPTER II.

## THE ACTION IN THE OTTO GAS ENGINE.

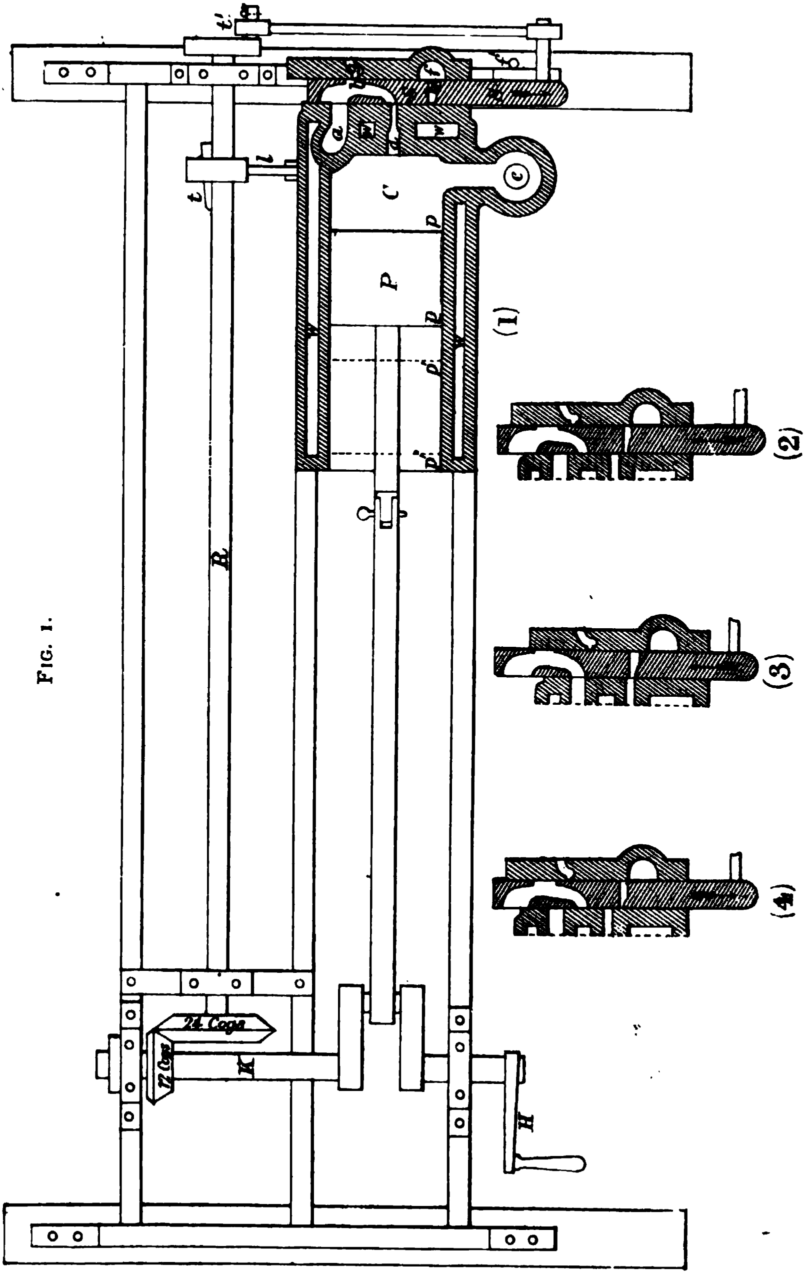
In answer to the question—What is the best way of presenting the subject of internal combustion engines to our readers? we have come to the conclusion that it is best to first describe carefully the action of some particular form of gas engine, for we consider that the ordinary reader would have considerable difficulty in understanding the significance of certain points in the history of this class of motor unless he were acquainted with the working of at least one of the best modern forms. Other modifications of this type of engine can afterwards be considered.

We have chosen to describe the most common type of internal combustion engine, which is known as the "Otto Gas Engine."

The sectional plan, Fig. 1, is taken from a model constructed in the workshops of the Finsbury Technical College, and enables us to follow the action of this engine. For the sake of simplicity it has been thought well, in a model of this kind, to omit all parts of the engine which are not absolutely necessary for a proper understanding of the different operations gone through when the engine is working fully loaded and at its normal speed of 160 revolutions per minute.

Instead of the handle H, by which one works the model, the student can easily imagine a fly-wheel and driving-pulley keyed on the crank shaft K. We have also done away with the slide on piston P, making the piston itself a slide. In the actual engine the cylinder is open at the end nearest the crank shaft, there being no stuffing-box. Part of the piston slides between guides made to fit it accurately. The piston is of great length, and as light as possible consistent with safety.

FIG. 1.



MODEL OF OTTO GAS ENGINE.

The wearing parts can be easily taken out and, when worn, replaced by duplicates.

The student is aware that the piston moves in a straight line, whereas the other end of the connecting-rod moves in a circle with the crank, hence in some steam engines there are parallel motions to allow the connecting-rod to move in this way; otherwise part of the push and pull which is being transmitted through the connecting-rod is wasted in pressing the piston-slide against the guides, causing considerable friction. However, in most steam engines, as in the gas engine, the piston is directly attached to the crank by the connecting-rod, thus dispensing with the parallel motion, in order to have the working parts few and simple.

It will be seen that when the piston P is as far back as it will go at the end of its stroke, as shown in the figure, position *p*, only what we call the clearance-space behind it in the cylinder C untraversed by the piston, is filled with gas. This clearance is about two-thirds of that part of the cylinder swept through by the piston. The fluid in it is a mixture of carbonic acid gas, water-vapour, oxygen, and nitrogen, remaining from previous combustions. The temperature of these gaseous products may be anything between 500° C. and the temperature of the atmosphere, depending on how recently an explosion has taken place.

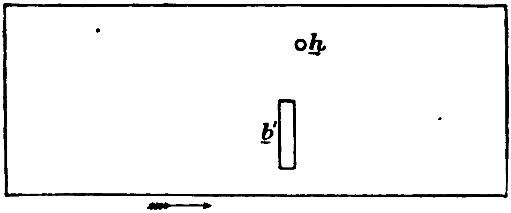
The cylinder is surrounded by a water-jacket W, through which water is kept continually circulating by means of two pipes leading to a tank at a higher level. A constant supply of water flows from the tank through one pipe to the bottom of the cylinder, circulates through the jacket to the top of cylinder, and back again to the tank by the other pipe. When the engine has been working for some time, the water leaves this jacket at a temperature of about 60° C. The tank radiates heat, and is made sufficiently large to remain quite cool during continuous working. Sometimes the water is taken directly from the street pipes, but it should be allowed to escape by a pipe from the top of the cylinder, and sloping upwards at every point, in order to keep the water-jacket always full when the engine is working. Now, as the piston moves forward from *p* to *p'*, it sucks in after it a mixture of air and gas through the inlet port *d*, to fill up the vacancy at end of cylinder.

The slide S allows free communication between the port *d* and the air and gas supply ports *a* and *g*, through the forked central passage *b*. At the first part of the stroke only air is admitted, next both air and gas, so that the mixture at the end of the cylinder is richer in gas and more explosive. Thus, when the piston reaches *p'*, the end of its forward stroke, the relative positions of the slide and ports is that shown in (2). All the parts at the back of the cylinder are fixed except the slide S. It is moved backwards and forwards by connection with a crank *t'* on the counter-shaft R, which is driven by gearing at half the speed of the crank shaft K. This causes the slide to move once forward and back during the four strokes of the piston. At the end of this forward stroke the pressure of the mixture of air, gas, and products of previous combustion, is nearly that of the atmosphere, 14·7 lb. per square inch, whilst its temperature is probably about 120° C.

In the return or back stroke the charge is compressed by the piston into the clearance space, as it cannot escape from the cylinder, all the ports being closed by the slide as in position (2). At the end of this compression, with piston again in position *p*, the pressure is nearly three atmospheres. The crank shaft has made one complete revolution.

The compressed charge is now fired by a very ingenious arrangement. The gas for this purpose does not come through the principal pipe which feeds the motor cylinder, but directly from the street main by another small pipe. This gives a steady supply to the flame *f* which is kept constantly burning, and the other little gas jet *f'* which communicates with the ignition chamber *b'* in the slide valve S, at one part of the stroke. Now as the slide moves to and fro, the little ignition chamber *b'* comes into communication with *f'*, gets filled with gas which is ignited in passing *f*, and the burning mixture is carried along, completely enclosed in the chamber *b′*; but before it reaches the port *d* something occurs. In the slide-valve, facing the end of cylinder, there is a small hole *h*,

FIG. 2.



SLIDE-VALVE IGNITION ARRANGEMENTS.

Fig. 2, a little in advance of *b′*. The distance is carefully determined by experiment and must not be altered. As the slide moves in the direction indicated by the arrow, this hole *h* makes communication, through a narrow T-shaped channel, between the passage *b′* and the interior of the cylinder by a small hole above *d*, Fig. 1. Part of the compressed gas rushes from the cylinder through *h* into the chamber *b′*, where it is ignited and increases the pressure; so that when the ignition chamber *b′* comes right up to the port *d*, as shown in (3), Fig. 1, the flame shoots into the cylinder and fires the compressed charge at the beginning of the next forward stroke of the piston, just as the crank shaft is passing the centre.

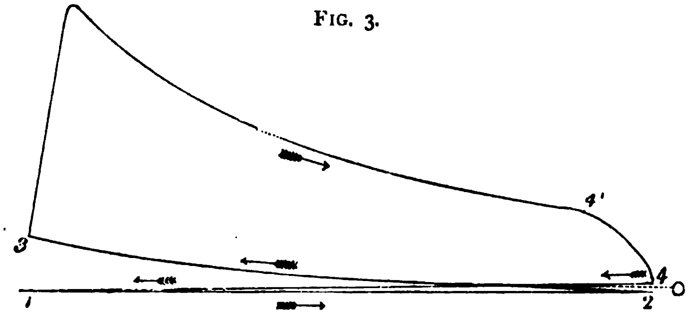
When the explosion takes place, the temperature suddenly rises to somewhere about 1600° C., and a great amount of heat is given out to the walls of the cylinder. Whether prolonged combustion is due to the mixture forming into layers at all temperatures, that in the centre and end of the cylinder being very hot, and the outside one in contact with the cylinder sides comparatively cool, and that then gradual combustion takes place from layer to layer; or whether the rate of combustion is controlled by dissociation of the combined gases, it is extremely difficult to say. At all events, rapid development of heat results, and the expanding gases drive the piston forward.

Combustion continues, but the water in the jacket runs away with the heat so quickly that the pressure gradually diminishes until near the end of this forward stroke; just before the piston reaches *p'*, and whilst the slide S is still covering the port *d* as in position (4), the burning gases are allowed to escape by the exhaust pipe *e*. On the counter-shaft R there is a cam *t*, which has acted on a lever *l* opening the exhaust valve in opposition to a spiral spring which holds it closed. The shaft R only makes one revolution for every two of the crank shaft.

In the next back stroke the piston drives the products of combustion out of the cylinder, with the exception of what remains in the clearance space untraversed by the piston, and thus completes a cycle of operations.

The energy that is stored up in the fly-wheel during the explosion and expansion of the charge is depended on to carry the engine through all the rest of the cycle, that is, enables the engine to reject the burnt products, to draw in and compress a fresh charge of air and gas, which is again fired, burnt, and expelled as before; there being only one explosion every second revolution when the engine is working at full power.

Fig. 3.



Indicator-diagram from Otto Engine.

We can easily follow these operations on an **indicator-diagram**, Fig. 3, taken from an Otto Engine. It will give us at once an idea of the alterations in pressure and volume of the gases in the cylinder, and on more careful study will, in fact, tell us all about the working of the engine.

The arrows indicate the directions of the piston's motion. Horizontal distances, measured from 1, represent, to a given scale, the distances in feet travelled through by the piston, and hence the volume occupied by the gases in the cylinder. Thus the line 1, 2, Fig. 3, corresponds to the length of travel of piston from *p* to *p'* in Fig. 1.

Distances measured vertically from the line 0, 1, Fig. 3, give us the pressure in pounds per square inch, above or below the atmospheric pressure, in the cylinder at any point of the stroke. The line 0, 1, is the atmospheric line, and the height above it to any part of the curve represents the pressure, above atmospheric, in the cylinder at that point in the stroke. Thus, **heights represent pressures, and horizontal distances the travel of the piston.**

Now starting, as we did above, with the piston in position (1), Figs. 1 and 3, we shall have the following operations:—

1. *Suction or Charging.*—The forward stroke of the piston from 1 to 2, Fig. 3, during which the slide S, Fig. 1, allows the charge of air and gas to be drawn through the passages *b* and *d*, into the cylinder. The line 1, 2, is slightly below 0, 1, showing that the pressure all along is less than atmospheric, owing to the vacancy left by the piston, and the cooling of the cylinder by the jacket-water, hence the great indraught of air and gas. At 2, Fig. 3, the inlet port *d* is closed by the slide, as shown in (2), Fig. 1.

2. *Compression.*—The line 2, 3, shows the compression of the charge by the back stroke of the piston from *p'* to *p*, Fig. 1. We see the line 2, 3, gradually rises, until near the end of the stroke, the height above 0, 1, represents a pressure between two and three atmospheres, notwithstanding the contraction due to cooling of cylinder by the jacket-water. One revolution of the engine is now completed. At 3, the crank has just passed the centre, and the piston is commencing its next forward

stroke as the ignition chamber *b'* comes up to the port *d*, and the relative position of the ports is that shown (3), Fig. 1.

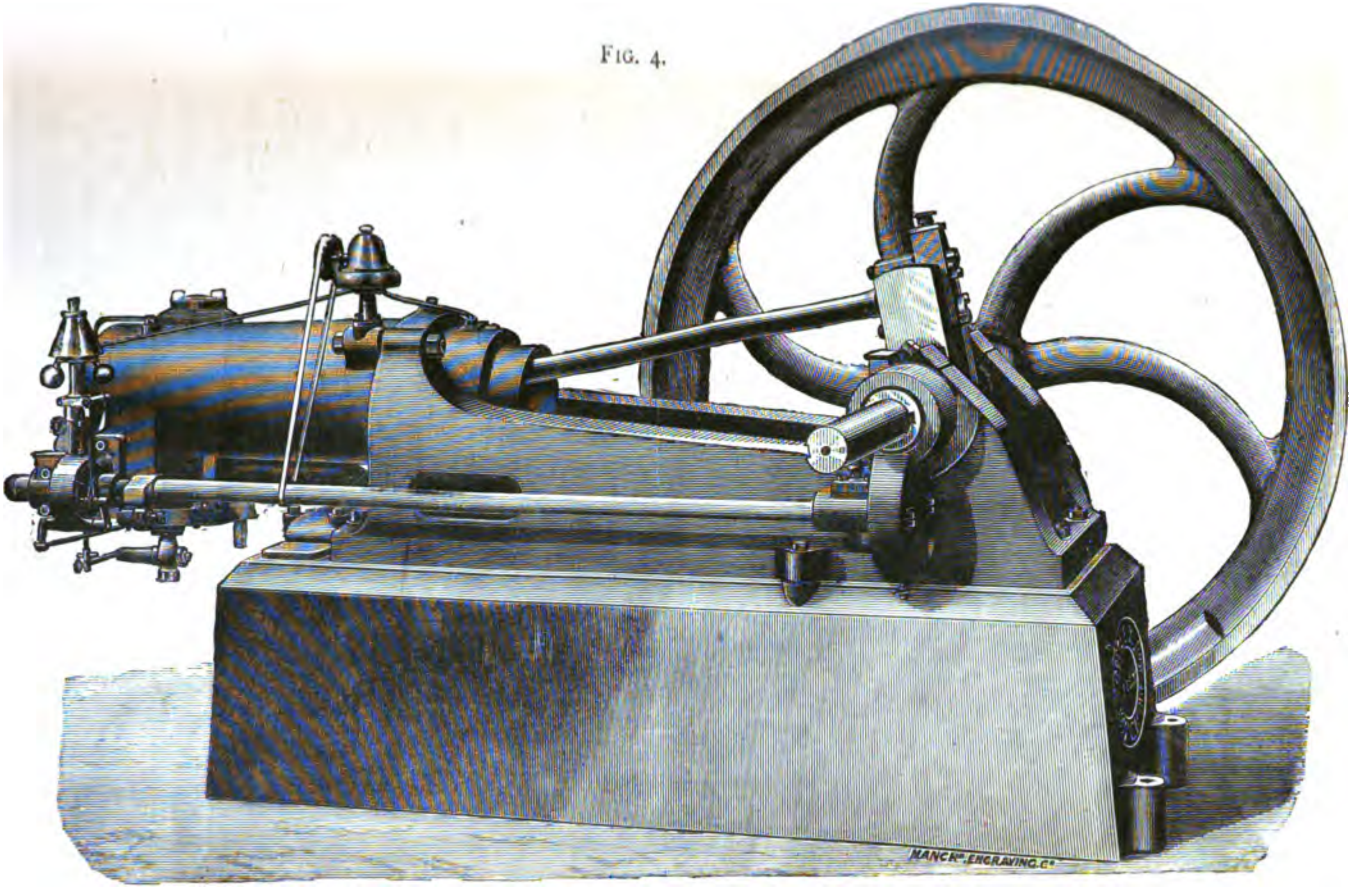
3. *Combustion and Expansion.*—At 3, we have ignition, explosion, the pressure rapidly rising and then gradually falling off as the gases burn and expand, driving forward the piston. Before the end of stroke at 4', the exhaust valve opens. In this operation the heat of combustion has expanded the gases, raised the pressure, and driven the piston, overcoming the resistance of the mechanism and getting up speed. This is the only part of the cycle in which heat is converted into work, hence it is called the working stroke.

4. *Exhaust.*—The line 4, 1, shows the pressure in the cylinder during the discharge of the products of combustion by the piston in its return stroke from *p'* to *p*.

We are now back at our starting-point. The engine has made two revolutions, and simply goes through the same operations over and over again when working at full power.

The explosions may take place much more rarely when the engine is running with a light load. Then comes into play the **governing arrangement**, not shown in the model, which allows more or less gas into the supply pipe *g*, depending upon the speed of the engine. On the shaft R there is a cam which, as it revolves, knocks up a little lever, and opens the gas supply-valve *g*, at the proper time, in opposition to a spring which quickly closes the valve as soon as the cam allows it. There are steps on the cam enabling it to vary the supply of gas by pressing up the lever a longer or shorter period of time. The centrifugal governor moves this lever to and fro, by means of a little roller, so as either to come in the way of the cam when the engine is working at proper speed, or to escape the cam so that the supply-valve is not opened, and there is no admission of gas when the speed is too great. Thus the governor-balls, as they rise and fall with the speed, completely control the supply of gas, and prevent unnecessary waste. On account of the demand by the engine for gas being sudden and intermittent, it is usual to have on the main gas pipe, as close to the engine as practicable, a flexible india-

FIG. 4.

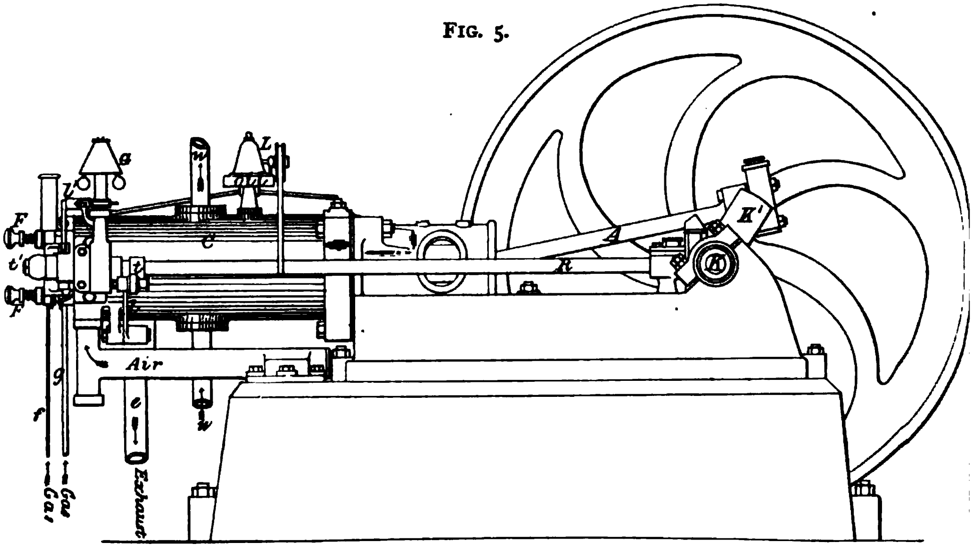


OTTO GAS ENGINE.

rubber bag, to act as a gas reservoir and give regularity to the supply required. A cast-iron gas bag with anti-fluctuator may also be used.

In studying the construction of a machine like the gas engine, the student would do well to examine an actual engine, make drawings of its several parts, and carefully observe its action for himself. The information gained in this way will amply repay him for the time and care expended.

FIG. 5.



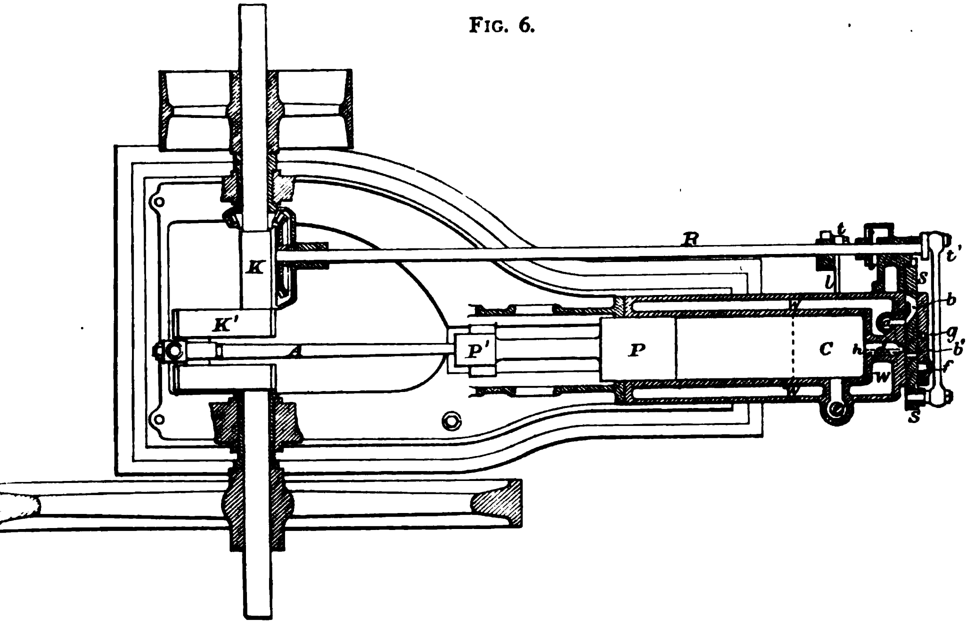
OTTO ENGINE (SIDE ELEVATION).

A good idea of the general arrangement of parts in a gas motor of this type can be gathered from Fig. 4, an external view of a nominal 7 H.P. engine; Fig. 5, a side view or elevation; and Fig. 6, a horizontal section of the ordinary pattern of Otto engine, whose action we have just been considering. We use the same reference letters in these as on the corresponding parts in Fig. 1.

One fly-wheel is omitted in the drawings, to avoid confusion. There are usually two fly-wheels, one keyed on each end of the crank shaft K, to balance the machine and give more regularity of speed.

The cylinder C is open to the air at the end next the piston-rod, and the piston-slide P′ which moves in this open space is attached directly to the crank K′ by the connecting-rod A. The jacket-water W surrounds the cylinder, and keeps its inner surface so cool that the oil can lubricate the piston. L is the lubricator, driven by an endless leather strap or belt off the countershaft R, and gives a constant supply of oil to the slide-valve S and piston P, through two little tubes, as shown in Figs. 4 and 5. It is all-important that the lubricator should not be allowed to run dry, else the slide-valve S is liable to be burned and injured from want of oil.

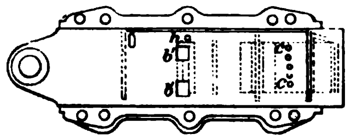
Fig. 6.



Otto Engine (Horizontal Section).

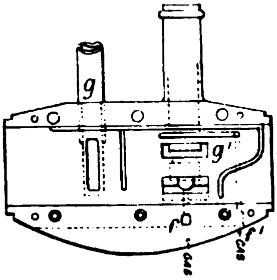
G is the centrifugal governor, and *l*′ the lever arrangement acted on by the cam, to regulate the supply of gas; *t*′ is the crank which actuates the slide-valve ; *t* is the cam and tappet which, acting on the lever *l*, opens the exhaust-valve, and allows the products of combustion to escape by the pipe *e*. The side shaft R, driven by bevel gear or worm gear from the crank shaft K, makes one revolution for every two of the fly-wheel, and opens the exhaust-valve *e* by the lever *l* ; it also actuates, by crank and arm *t'*, the **slide-valve** S, which alone simply, yet ingeniously and effectually, serves for the *admission*, *distribution*, and *ignition* of the charge.

FIG. 7.



SLIDE.

FIG. 8.



SLIDE COVER.

This slide, Fig. 7, works between the face plate on the end of the cylinder and a cover, Fig. 8, which is pressed against it by two spiral springs F, F, Fig. 5, under two nut screws, keeping the slide in its place close to the back of the cylinder, so as to prevent leakage of gas therefrom.

The main gas supply pipe *g*, and the air-passage *a*, communicate at the proper time through the slide passage *b* with the port *d*, which leads into the cylinder. A separate gas pipe *f* feeds the two slide lights, the one *f* in the slide-cover is continually burning in the open air in the lower part of chimney, shown in figure ; the other *f'* is intermittent and relighted, after each explosion, by the fixed burner.

A groove *g'* is formed in the slide-cover, and receives gas by a separate pipe ; it is closed by the slide except when the lighting port *b'* comes opposite to it, then *b'* is supplied with gas through the groove *g' f'*. The hole *h* in the cylinder face is the equilibrium lighting port, and level with it there is a narrow conduit *h* in the slide, as well as two holes *k*, Figs. 11 and 12. In this way there is free communication between the cylinder and *b'*, a little before it is brought up to *d'*.

All these passages and holes in the slide should be carefully cleaned at least once every 60 hours' continuous running. The slide valve must also be kept well oiled. In fact, if ignorant or careless attendants neglect the oil supply, or allow dirt to fall on the working surfaces, the slide ignition valve may at any time during a run get burned, cut, or scored, and so stop the engine. To overcome this fault and make the engine more reliable under all circumstances, slides are now dispensed with entirely by Messrs. Crossley, and an arrangement (see page 231) adopted for *ignition by a heated tube.* The ignition is accurately timed by a valve which opens communication between the rich compressed mixture in the cylinder and the red-hot tube at the right moment. This ignition valve is controlled by a lever from a cam on the shaft.

In order to get ready for **starting the engine**, we turn on the water by the tap at the tank, so as to have it circulating in the water-jacket round the cylinder by the pipes *w*, *w*, Fig. 5. Next move the governor G to its middle position, and fix it there by putting the little prop underneath it. Now it is difficult to turn the fly-wheel during the compression part of the stroke, unless the exhaust valve is kept open. For this purpose, change the pin which secures the cam *t*, and move the cam along the shaft that it may act on the exhaust valve lever every half revolution. Move the exhaust valve lever by hand to let out any gas or air that may have accumulated in the cylinder and passages. Light the gas jet *f*, and the inner or slide light *f'*. Then fill the gas bag behind the engine, and shut off the main supply of gas. Lastly, open the gas cock on the cylinder, and give the fly-wheel a few sharp turns. When an explosion takes place, and the engine starts, turn on the main gas supply and push back the cam *t* to its proper position. If the engine be clean and properly oiled, it requires no further attendance, but works safely and steadily, and is stopped by simply turning off the gas. This plan of keeping the exhaust open while starting entails the danger of an explosion in the exhaust pipe, hence with large engines the exhaust is not opened in this way for starting.

Engines above 20 indicated H.P. usually have SELF-STARTING APPARATUS attached, which saves us the trouble of pulling round the fly-wheel to get in the first charge. The earliest device for starting the Otto engine consists of a strong receiver or accumulator into which some of the burnt gases pass when a certain pressure is reached during part of every stroke when the engine is running, until the pressure in the accumulator is raised nearly to the highest attained in the cylinder, upwards of 100 lb. per square inch above atmosphere. The burnt gases pass to the accumulator through a loaded valve fitted with an oil trap arrangement, which prevents leakage, so arranged that the gas can be kept under great pressure for a considerable period of time. When it is desired to start the engine with the crank just over the centre in the explosion stroke, we have only got to open a valve by hand, the stored gases are admitted to the cylinder at great pressure, act on the piston, and set the engine in motion, just in the same way that steam starts a steam engine. When gases are stored-up under great pressure, it is very difficult to avoid leakage, and fall of pressure also, due to cooling; besides, there is always the possibility of explosions if much combustible gas is present amongst the burnt products, and the danger of the reservoir bursting with fatal consequences.

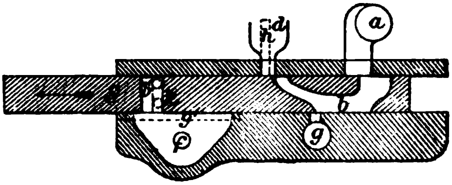
In unskilled hands these accumulators are not found to be satisfactory. Hence Messrs. Crossley use a small special gas engine to drive a shaft carrying a friction bowl of compressed paper, which is held against the fly-wheel face by means of a lever, and so drives the largest engines of 40 to 120 indicated horse power without load, until explosions take place in the cylinder to get up speed.

The **Action of the Otto engine** is as follows :—

Fig. 9 shows the position of the slide going in the direction of the arrow at the beginning of the forward charging stroke, when the piston is at the point indicated by the dotted line, Fig. 6. As the piston moves forward, air is drawn first from *a* into *b*, where it mixes with gas afterwards admitted from *g* through a series of holes *c c*, Fig. 7, so arranged as to have the mixture of any desired strength, and to let the gas enter a little after the air port is shut.

The idea was to have the charge at the moment of ignition not quite homogeneous: the mixture being rich in gas near the slide port, but poorer and mixed with the residual products near the piston. This has been abandoned, for it is evident, when one considers the great velocity with which the incoming gases enter the cylinder, there must result a thoroughly homogeneous mixture before ignition takes place.

FIG. 9.



ADMISSION OF CHARGE.

Whilst in the position shown, Fig. 9, the mixture is passing on through the other end of the passage *b* into the cylinder by *d*. The lighting port *b'* is receiving gas from the groove *g'*, and this is burning in connection with the flame *f* in the chimney. This continues while the line 1, 2 of the **indicator diagram,** Fig. 10, is being traced, until the piston reaches position P, Fig. 6. (The arrows on the diagram indicate the direction of the piston). The pressure is somewhat less than atmospheric, owing to the vacancy left by the piston and the cooling effect of the jacket-water, hence the suction and rapid inrush of air and gas. At 2, Fig. 10, the port *d* is closed by the slide, and the return stroke of the piston compresses the charge along the line 2, 3, to a pressure which may be 40 lb. or 60 lb. per square inch.

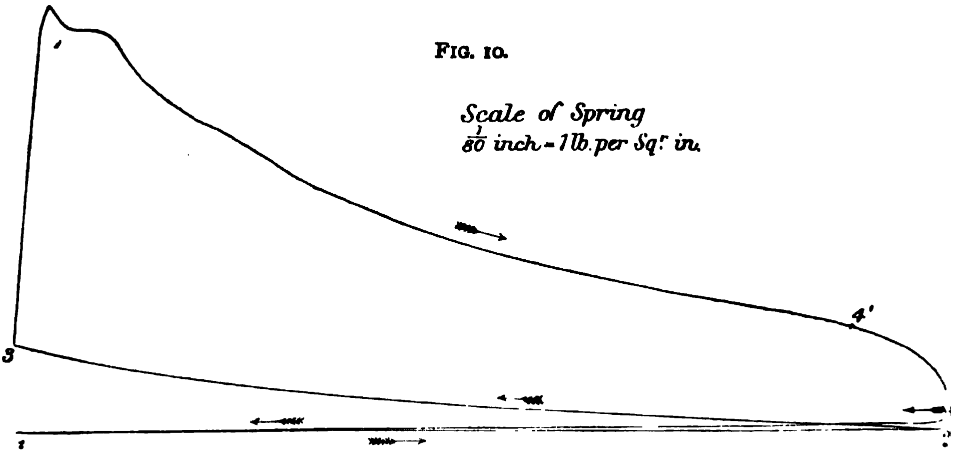
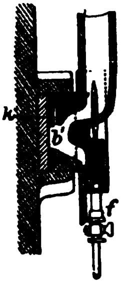


FIG. 10.

INDICATOR DIAGRAM FROM A 16-H.P. OTTO ENGINE.

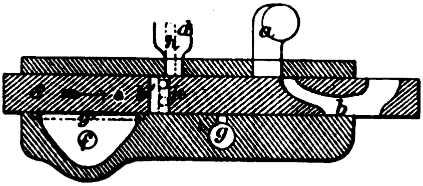
Meanwhile the mediating flame in the lighting chamber *b'* has been prepared to ignite the compressed charge. As in Fig. 11, gas was supplied to it from the groove *g'* in the cover through the little conduit *k*, and ignited by the burner *f*; afterwards this is cut off as the chamber *b'* filled with the lighted gas is carried to the right, past *g'* and isolated; then before *b'* is brought opposite to *d*, it is placed in communication with the cylinder C by the little narrow holes *h* and *k*, through which a small portion of the rich compressed charge from the cylinder enters to strengthen the flame and gradually raise the pressure in *b'* up to that in the cylinder C. The burning mixture in *b'* expands, its pressure rises even higher, and when the slide arrives in position, Fig. 12, the next forward or working stroke is just beginning, *b'* shoots a tongue of flame through *d* and fires the rich compressed charge near the port, the cylinder being now completely closed by the slide. The rich mixture near the end of the cylinder burns first, and the flame spreads through the rest of the charge gradually whilst the piston moves forward. The rate of combustion and consequent increase of pressure is completely under control by the dilution and compression of the mixture as well as by the way in which this mixture is fired.

FIG. 11.



LIGHTING CHAMBER.

FIG. 12.



PLAN OF SLIDE-VALVE.

The maximum temperature reached is probably about 1600° C.; the pressure rises as indicated by the line 3, 4', 4, Fig. 10, whilst the burning gases expand, driving the piston forward during the working stroke.

It has been calculated that about half the total heat of combustion of the charge is developed as heat at the time when the maximum pressure is produced in the cylinder, the rest being developed afterwards. The gradual and prolonged combustion should be as complete as possible when about 4', Fig. 10. The tappet *t*, Fig. 6, opens the exhaust valve *e* by the lever *l*, and allows the burnt gases to escape above 400° C., and the return stroke of the piston expels them at atmospheric pressure, as shown by the line 4, 1. The piston only comes as far as the dotted line, Fig. 6, so that part of the burnt products are left in the clearance space at the end of the cylinder not swept by the piston.

The water-jacket cools the cylinder, whilst a fresh charge of air and gas is *sucked in* and mixed with the residual products, *compressed*, *burned*, and *expelled* as before. Thus we have one explosion every two revolutions, whilst the slide moves once forward and back again.

The Crossley engine can readily be adjusted or altered from the normal for coal gas to use Dowson gas and oil gas. No alteration is made for rich oil gas beyond reducing the size of the "*gas-check*" to suit the quality of gas used, in order to have the proper richness of mixture. Dowson gas has only about one-quarter the explosive energy of ordinary coal gas, so that to obtain the same strength of mixture when working with Dowson gas as with coal gas—that is, to enable the engine to do as much work—it is necessary to increase the gas supply fourfold, diminish the air supply, and increase the compression.

FIG. 13.

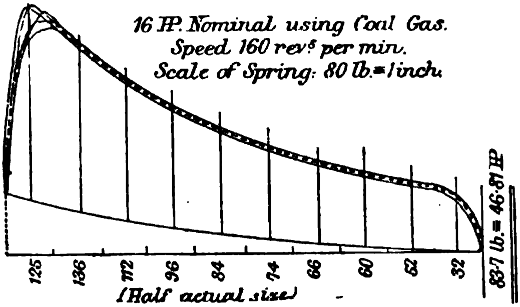


DIAGRAM FROM CROSSLEY ENGINE.

The indicator card, Fig. 13, is a fair sample (half-size) of that obtained from a 16 H.P. nominal engine using coal gas. It shows 46·8 indicated horse-power. A similar 16 H.P. engine working with Dowson gas gives the card shown in Fig. 14. Here the compression is greater and the indicated horse-power less than with coal gas. With Dowson gas the cost of power is greatly reduced, recent results showing a consumption of $1\frac{1}{16}$ lb. of coal per indicated horse-power per hour.

It is always desirable, and for many purposes—as electric lighting, &c.—absolutely necessary, that a prime motor should run steadily, at uniform speed, with widely varying loads. Impulses or shocks which suddenly vary the speed and destroy the mechanism unless of excessive strength, are very objectionable, and in fact constituted one of the greatest drawbacks in the early forms of internal combustion engine. Some types of the modern gas engine are so arranged that an explosion can be made every revolution, but even in these the governor must modify the action somewhat. In our typical example—the Otto engine—we have had only an explosion every alternate revolution, yet this engine is found to work without much variation of speed under the control of a sensitive centrifugal governor arrangement for regulating the supply of gas.

FIG. 14.

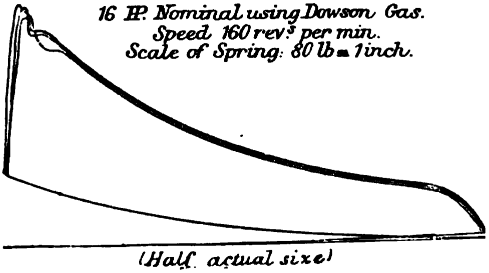
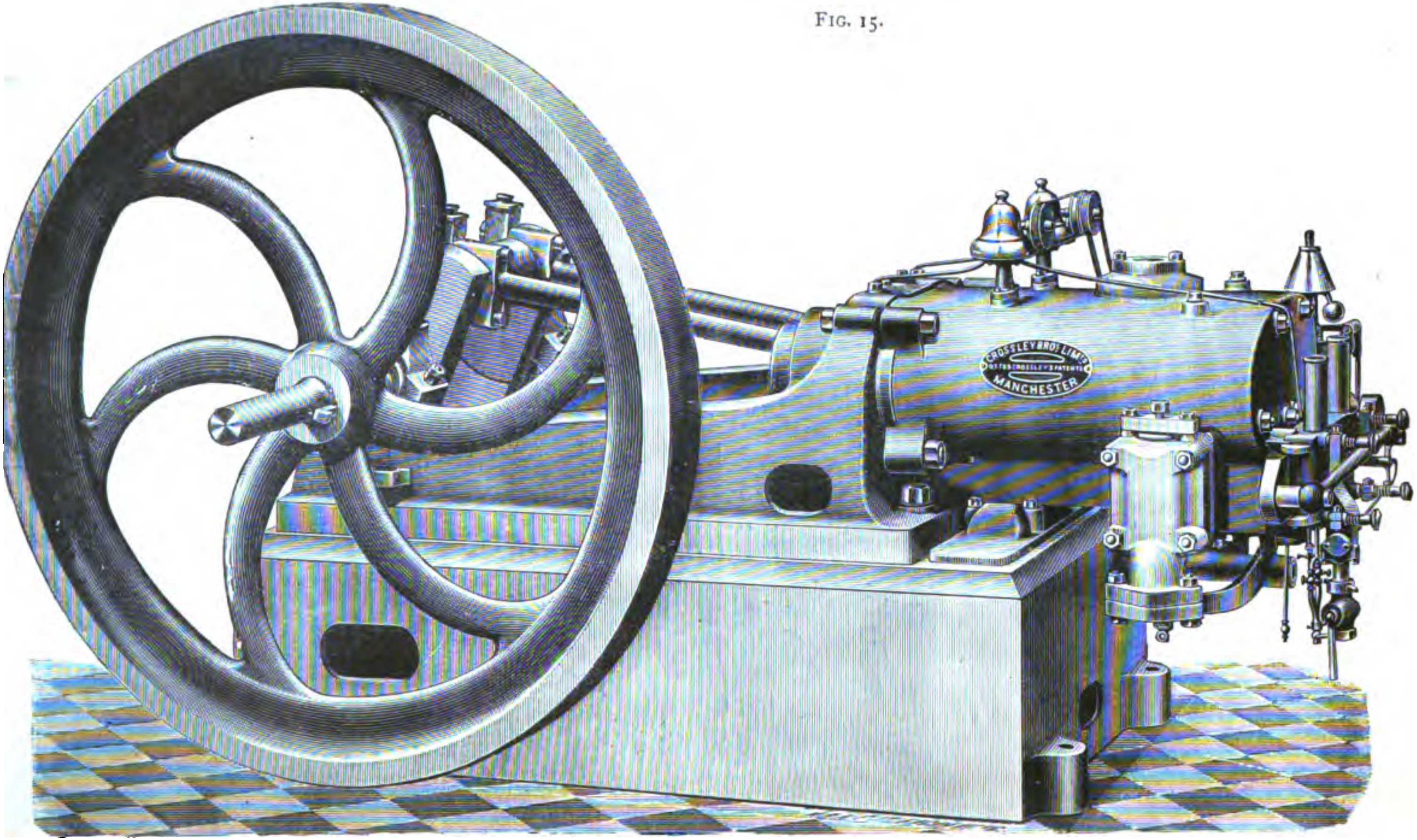


DIAGRAM FROM CROSSLEY ENGINE.

The simplest and most effective governor is that which cuts off the gas supply completely for one or more cycles, and thus diminishes the number of impulses given to the piston when the speed becomes too great. For electric light purposes, where regularity of speed with slightly changing loads is most important, the ordinary method of governing is too irregular, and it is found better only to diminish the supply of gas, and thus lessen the energy of each explosion as the speed increases. A centrifugal governor works a cam made in three steps upon the shaft. This cam acts on the gas-lever, and according to its position on the shaft will be

FIG. 15.



CROSSLEY TWIN-CYLINDER GAS ENGINE.

the particular step of cam that engages the gas lever and the amount of gas cut off. In this way the power of the engine is reduced as the speed increases under a light load, so that the same number of impulses being still given the speed is kept fairly uniform. The card, Fig. 16, shows what takes place as the strength of the mixture is diminished until the charge misses fire and there is not an explosion as the large, medium, and small steps on cam engage the lever.

FIG. 16.

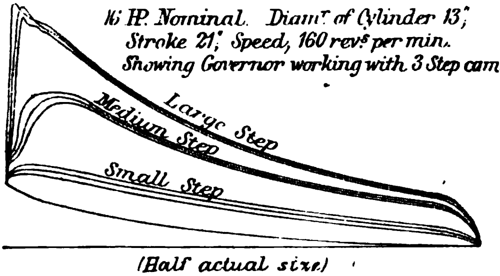


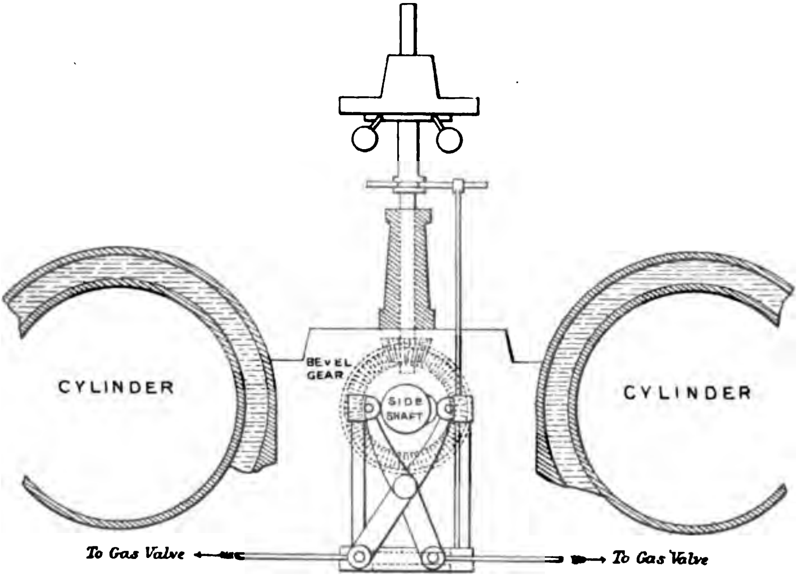
DIAGRAM FROM CROSSLEY ENGINE.

The usual speed of all sizes is 160 revolutions per minute. To render this still more uniform and to give better regularity for high powers, the **Crossley twin engine** was devised, Fig. 15, in which two precisely similar engines are coupled. The early form, Fig. 15, had a single slide valve for the supply and ignition of the two charges. The two cylinders were placed side by side within one and the same water-jacket, and their pistons were both coupled to the same crank, so that they moved together.

In the 1888 design of the Crossley double-cylinder engine, to be seen in the front of this book, the cylinders are apart, each with its own water-jacket. **Slides are entirely given up**; separate valves, lifted by levers and cams against spiral springs, are used instead. The side-shaft between the cylinders is driven by worm gear from the main shaft, and carries cams which work the air-admission, ignition, and exhaust levers. The gas supply is, as usual, regulated by a weighted governor, Fig. 17, which is worked by bevel gear from the side-shaft, and moves a roller along a separate spindle (compare Fig. 17 and frontispiece) to admit or cut off gas by acting on the gas-valve levers.

Hot tubes are used for firing, accurately timed by levers acting on the ignition valves (see page 230), so arranged that when the engine is working at full power the charges are fired alternately in the two cylinders, and there is an explosion every revolution of the driving shaft.

FIG. 17.



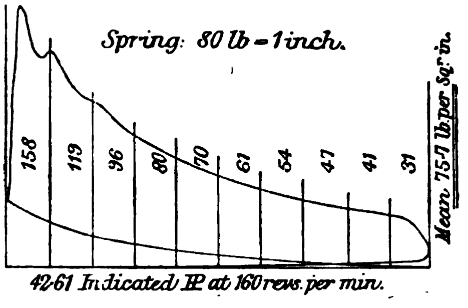
CROSSLEY GOVERNOR GEAR.

The two piston-rods are connected to the driving shaft by cranks opposite each other, so that when one piston is commencing its compression stroke the charge is being fired in the other cylinder driving forward the other piston. While the piston of the one cylinder is making its forward stroke, drawing in the charge, the piston of the other is going in the opposite direction, compressing the charge in its cylinder; and while the former is making its back stroke, compressing its charge, the other is being driven by the combustion and expansion of gases during its working stroke; the next stroke is firing in the first cylinder and exhaust in the other, and so on.

The products of combustion are expelled through ordinary cast-iron pipes into a cast-iron chamber partly filled with fine shingle (flint pebbles) in a brick-pit, in order **to diminish the noise of the exhaust.** This can also be done in other and simpler ways. From this pit the burnt products pass through a wrought-iron ventilating pipe into the open air.

One automatic lubricator acts for both cylinders.

FIG. 18.



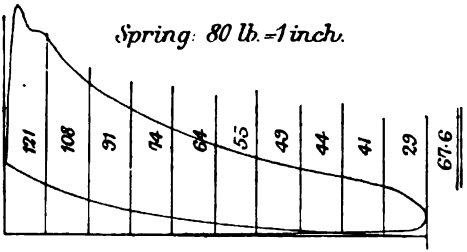
INDICATOR DIAGRAM (RIGHT-HAND CYLINDER).

There are two large-fly-wheels, and the regularity of speed is very satisfactory.

The double-cylinder 16 H.P. nominal Crossley engine works regularly and quietly with Dowson gas, giving upwards of 80 indicated horse-power for about 1·1 lb. of anthracite coal per indicated horse-power per hour. The two cards, Figs. 18 and 19, were taken at different times from the two cylinders.

The two great faults, or sources of waste, which the Otto has in common with most other gas motors, when regarded from the heat engine point of view, are : **first,** the temperature of rejection of the heat in the products of combustion into the exhaust is much too high ; and **second,** a large portion of the heat is lost through the walls of the cylinder to the water-jacket. In fact, the water in the jacket runs away with nearly one-half of the total heat that might be generated. Notwithstanding this loss, enough heat is supplied by gradual, prolonged combustion to do the work, and at the same time sustain the pressure, so that the expansion curve obtained in practice sensibly coincides with the adiabatic. As the temperature of the water-jacket is increased, the efficiency of the engine becomes higher.

FIG. 19.



*38·05 Indicated HP. at 160 revs. per min.*

INDICATOR DIAGRAM (LEFT-HAND CYLINDER).

With ordinary coal-gas of average quality, the **consumption** may be taken at 20 cubic feet per hour per indicated horse-power, or 24 cubic feet per hour per brake horse-power, including the constant gas supply for ignition. This last item is of course inappreciable when a large engine is used. When burning Dowson gas, the quantity of anthracite coal required is reduced to about 1·3 lb. per indicated horse-power per hour for ordinary regular working ; with the largest twin-engine, indicating about 100 horse-power, only 1·1 lb. of anthracite coal is required per indicated horse-power.

The **mechanical efficiency,** that is, the ratio of the useful brake horse-power to the indicated horse-power, is usually as high as 85 per cent., the remaining 15 per cent. being spent in overcoming the friction of the mechanism. The larger sizes of engines will give a little better results, the smaller ones a little worse.

For very small powers, a special *vertical* Crossley engine is used. This handy little domestic motor is fitted with a sensitive pendulum governor, which regulates the speed by cutting off the gas to suit the load. Such an engine can be quickly started and stopped at a moment's notice as required; and so long as the oil supply lasts, the engine does not need any attention while running.

Single-cylinder horizontal engines are made of any power varying from 2 up to 40 or 50 indicated horse-power. The twin-engines give twice this power, that is, up to about 80 and 100 indicated horse-power.

Many thousands of these Otto engines, as manufactured by Messrs. Crossley Brothers, have come into common use and as they are found to be convenient, safe, and economical, their application for industrial and domestic purposes is still extending rapidly.

# CHAPTER III.

## MODIFICATIONS OF THE OTTO TYPE OF GAS ENGINE.

THE *four operations* which constitute the cycle of the Otto compression engine are precisely the same as described by BEAU DE ROCHAS, in his patent of 1862, and pamphlet published in Paris the same year.

In one end of his engine cylinder the series of operations during four consecutive strokes of the piston, takes place in the following order:—

1. *Suction* or drawing-in charge, during the entire outward stroke.
2. *Compression* during the return stroke.
3. *Ignition* at the dead point, and *expansion* during the next forward stroke.
4. *Exhaust*, or *expulsion* of the burnt gas from the cylinder, during the last return stroke.

At the same time BEAU DE ROCHAS laid down the four conditions necessary to realise the best or most economical results from the elastic force of gases in his gas engine:—

1. Greatest capacity of the cylinder with least bounding surface.
2. Piston speed as high as possible.
3. Early cut-off, or as long range of expansion as possible.
4. High initial pressure.

The idea clearly is to use a cylinder of large diameter with high speed of piston, to prevent loss of heat by cooling; whilst *compression* of the gaseous mixture, in the cold state before ignition, gives high initial pressure, and this combined with long range of expansion utilises the largest proportion of the heat-energy in the gas.

From a practical point of view, a great advance was made in 1876 by the invention of the "Otto Silent," but since the details of this engine were perfected by Messrs. Crossley, gas engine practice remained in substantially the same position; and, considering the perfect workmanship and finish, there is little hope of getting much beyond the point already attained, working on the same lines.

## Atkinson's Engines.

The year 1885 marks an important step in the development of our motor, by the invention of ATKINSON'S DIFFERENTIAL Gas Engine.

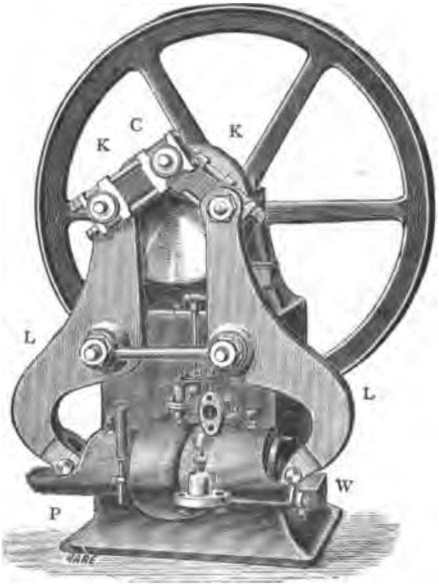
Mr. Atkinson has been devoting the whole of his time and inventive skill to gas engines. His first patent, dated 1879, No. 3213, was for a compression gas engine. This is noteworthy as being one of the *first known* instances of a *gas engine working with a hot tube ignition* almost identically the same as that in use at the present day.

In 1881 he patented improvements in the non-compression engine, and by ignition immediately after admission every revolution, effected considerable economy. He also worked for years with compound compression engines, but his experience led him to give up this idea and to perform the whole of the expansion in one cylinder. He tried a pump, consisting of the inner end of the working cylinder, and with an impulse every revolution; also, one with a separate pump, and in this way obtained high efficiency, which compared favourably with other engines in the market.

He made it his business to study thoroughly the theory of the gas engine, and after having attended a course of lectures by Professor Perry on the subject, at the Technical College, Finsbury, he saw, and had forcibly impressed upon his mind, that to make any decided improvement, it would be absolutely necessary to strike out in a new direction.

Realising the two great sources of waste as the **water-jacket** and the **exhaust**, he made up his mind that his next engine should do the work very quickly, hence the "differential" did it in *one-fourth* the time of any other engine, that is to say, the working agent in the cylinder expanded to *double its original volume in half the usual time.*

FIG. 20.

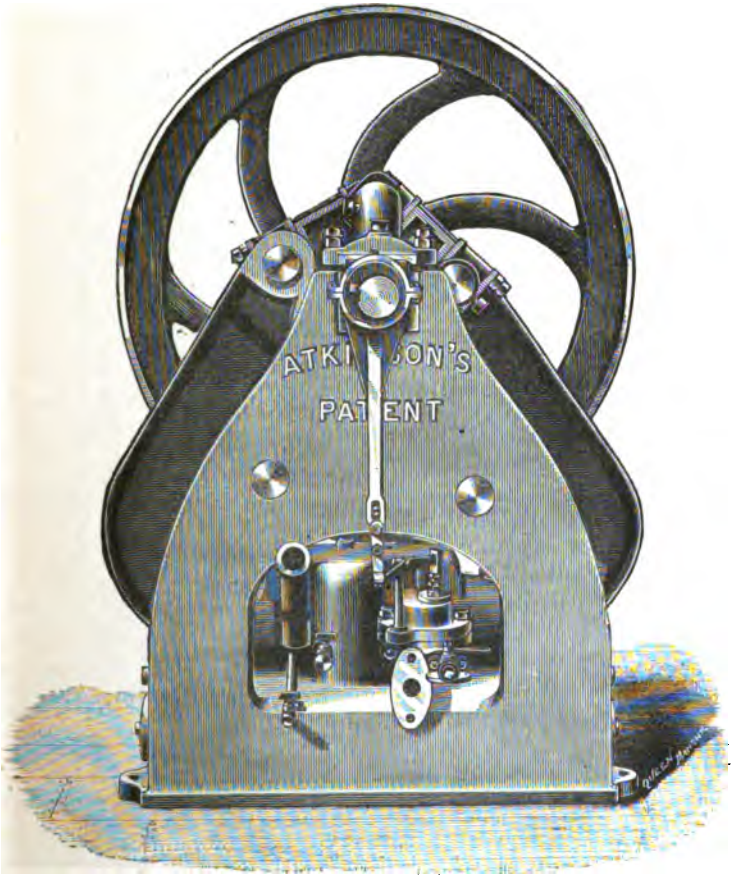


ATKINSON'S "DIFFERENTIAL" ENGINE.

The external view, Fig. 20, shows the general appearance of the first ATKINSON "DIFFERENTIAL" ENGINE, made hurriedly for the Inventions Exhibition, 1885. Its appearance was a surprise: and this is scarcely to be wondered at, when the patent was taken out, the engine designed, patterns made, and the first engine working in the Exhibition, all within one month. It attracted much attention by its novel motion, its simplicity, and the great advance it marked in the development of gas engines on the lines indicated by theory.

In this first engine the one cylinder, used both as pump and working cylinder, is fixed outside the framing, but in the next design, shown in Fig. 21, also in plan and section Figs. 22 and 23, the cylinder is placed inside, thus rendering the machine better balanced. This horizontal cylinder, Fig. 20, is open at both ends, and fitted with two pistons—the left hand one we shall call the pumping piston P, and the right hand one the

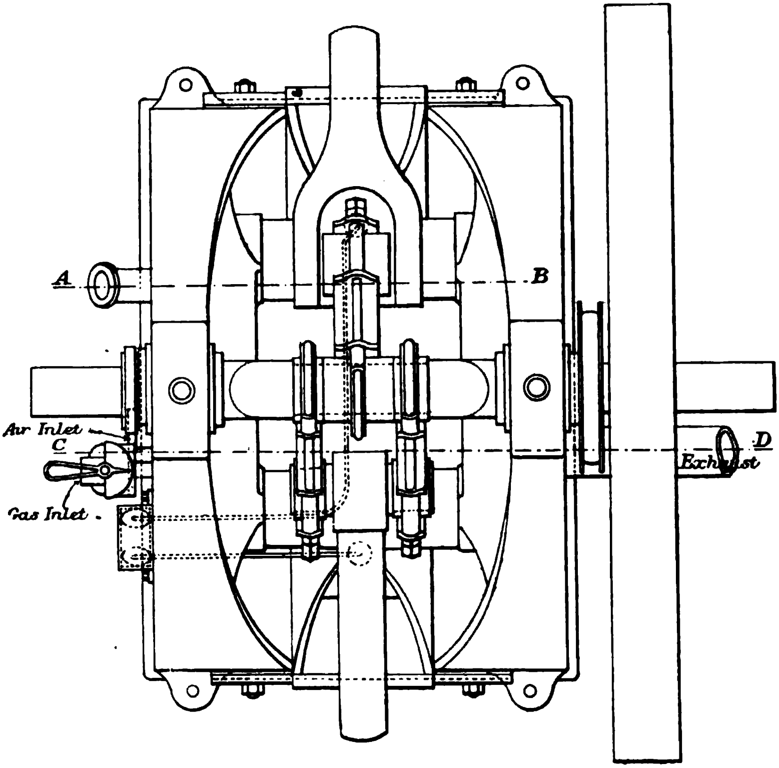
FIG. 21.



ATKINSON'S "DIFFERENTIAL" ENGINE.

working piston W. The pistons are connected by links to the lower ends of the levers L, L, working on the centres F, F, fixed in the main framing of the engine. These levers are attached at their upper ends by short connecting rods K, K, to one crank pin C, fixed in a disk which is keyed on the main shaft. These short connecting rods are an essential feature of the design, for it is the angularity of the rods and levers that causes the peculiar differential motion of the pistons.

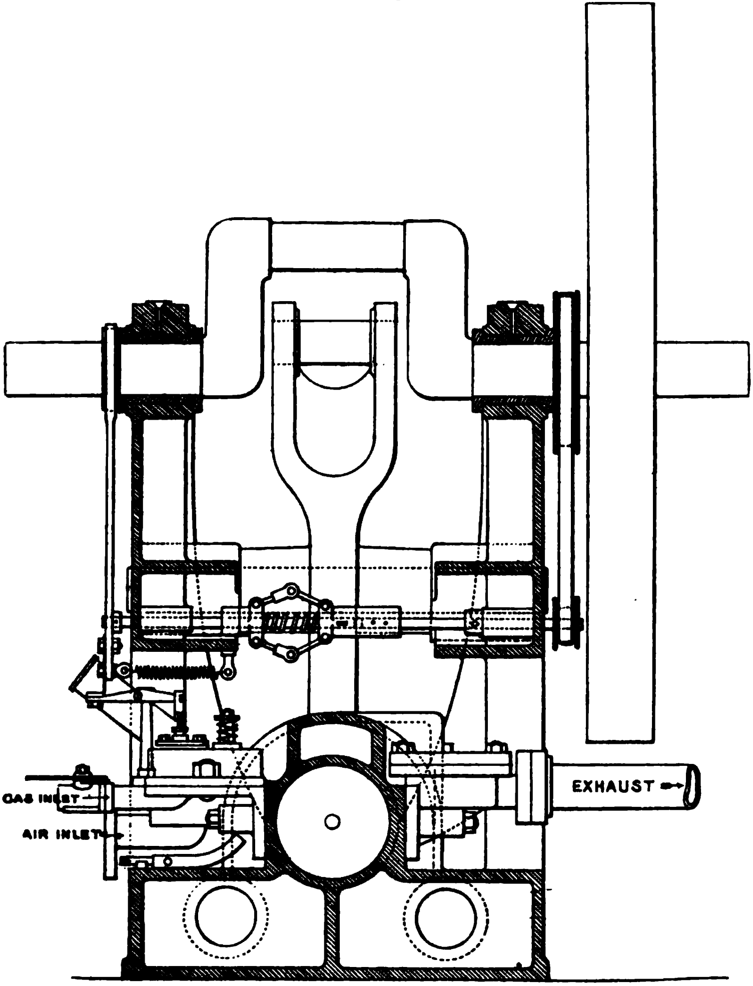
FIG. 22.



ATKINSON'S "DIFFERENTIAL" GAS ENGINE.

The plan and sectional elevation, Figs. 22 and 23, show the arrangement of working parts in the second design of the Differential engine.

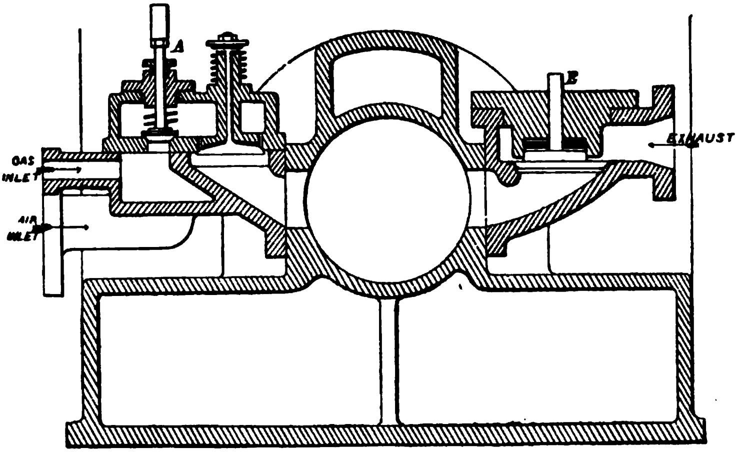
Fig. 23.



Atkinson's "Differential" Engine (Sectional Elevation).

Self-acting valves A and E, Fig. 24, prevent the air, gas, and exhaust passing in the wrong direction, whilst the sensitive centrifugal governor G, Fig. 23, controls the admission of gas. Except this governing gear there is not an eccentric or cam in the engine; the suction and exhaust valves are automatic, whilst the pistons do the work of the ordinary slide-valve, thus dispensing with the slide working-valve gear and the other usually complicated parts and adjustments, such as the delicate and intricate details in the slide-valve already described. This simplicity of parts is one of the most important points in the design. All previous practical gas engines were very delicate machines; slide-valves required to be fitted and adjusted with the greatest accuracy; any neglect in lubrication, or too great pressure in screwing-up, was likely to cause abrasion, throwing them out of order, and such engines could only be repaired by the makers, or engineers who had a lot to learn before they could repair or work them. Whereas the wearing parts in this engine are only pistons, and round pins with their bearings. The latter are made adjustable for wear, and have a large area of bearing surface so as to last long, and when worn an ordinary engineer can repair them.

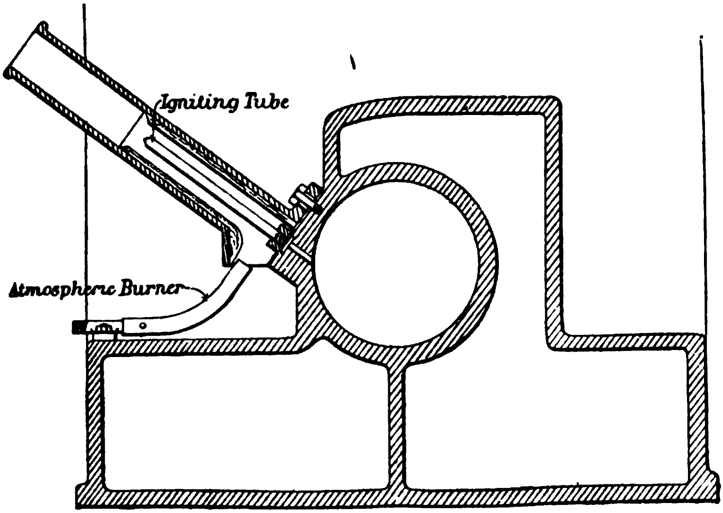
FIG. 24.



SECTION ON C D.

The *igniting tube*, Fig. 25, of wrought iron or ordinary gas pipe, is open at its lower end to a small hole drilled through the wall of the cylinder and closed at its upper end. It is kept red hot near the cylinder by a gas burner, so that when the pumping piston P uncovers the small hole, a portion of the charge rushes into it, is ignited, flashes back into the cylinder and fires the charge. These ignition tubes, when made of wrought iron, get burnt into a granular state, become choked up, and require frequent renewal; their average life in this engine being 180 hours.

FIG. 25.



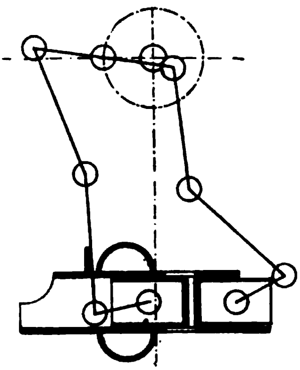
SECTION ON A B.

The middle part of the cylinder is surrounded with a water-jacket, but *owing to the increased rate at which the work is done, and the increased expansion, a much smaller quantity of water than usual suffices.*

The diagrams, Figs. 26, 27, 28, 29, show the position of the various parts of the engine at four points during one complete revolution of the main shaft, and fully explain the differential motions of the two pistons.

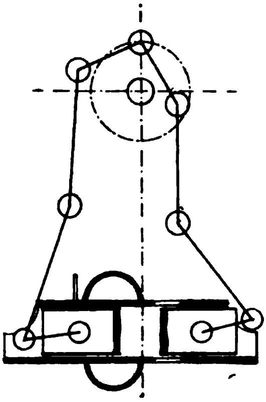
In Fig. 26 the two pistons are close together at one end of the cylinder, all the residual products of combustion from previous charges being entirely expelled; so that in this engine a fresh start is made every revolution, and one has not to consider any burnt products left over from the previous stroke, whilst premature ignition is also prevented without requiring a scavenging charge.

Fig. 26.



Termination of Exhaust.

Fig. 27.



Capacity for Charge.

Diagrams of Differential Gas Engine.

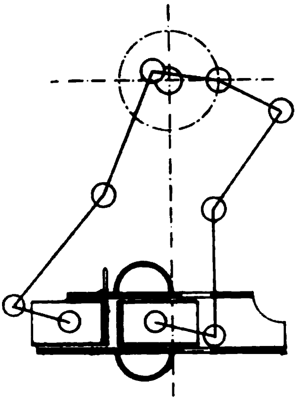
During the quarter revolution from position Fig. 26 to Fig. 27, the pumping piston P has moved rapidly away from the working piston W, leaving a considerable space between them which is filled up with a uniform combustible mixture of gas and air drawn in automatically through the self-acting suction-valve A, the passage to which is represented by the open space in the black lines at the top of cylinder.

The distance between the pistons here indicates the capacity of charge.

As soon as the crank pin moves beyond the position shown in Fig. 27, the working piston W passes the openings to the valves, shutting the charge in between the pistons and the cylinder walls, where it is kept until after the whole work is done, clear of all passages or valves, and consequently the area of the containing surfaces is reduced to a minimum, as also the loss of heat to the water in the jacket.

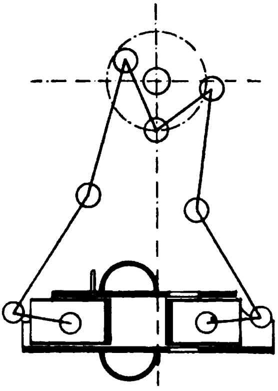
At this moment the pistons are travelling both at the same speed and in the same direction; but about this time the working piston W begins to travel faster, with the result of transferring the charge to the igniting end of the cylinder, and compressing it as the pistons approach each other, until they arrive at the position shown in Fig. 28, when the charge is compressed to any desired pressure, say 45 lb. per square inch.

FIG. 28.



CAPACITY FOR COMPRESSION.

FIG. 29.



CAPACITY FOR EXPANSION.

DIAGRAMS OF DIFFERENTIAL GAS ENGINE.

At this point the charge is ignited by the pumping piston passing and uncovering the opening to the ignition tube, which is kept red hot by an external atmospheric burner. Very rapid expansion of the ignited charge now takes place, causing an immediate working stroke by the working piston, which continues until the crank pin arrives at the bottom, as shown in Fig. 29, when the exhaust is allowed to take place by the working piston passing the exhaust port, and lifting up the self-acting exhaust valve.

During this working stroke, the pumping piston remains almost stationary, not having moved more than one-eighth of an inch, and acts as a cylinder cover, whilst the expansion has taken place to the original volume, and the pressure fallen to about 30 lb. But the expansion is continued until the space between the pistons is nearly double that into which the charge was drawn, and, therefore, the expansion is continued to nearly twice the original volume, when the pressure has been reduced to about 10 lb. All the work done during this continued expansion is a clear gain.

From the position in Fig. 29, the pumping piston follows up the other, and drives out all the products of combustion by the exhaust till the original state of things in Fig. 26 is again reached, and *the whole cycle completed in one revolution.*

It is evident that the total expansion to twice the original volume takes place, from Fig. 28 to Fig. 29, in a quarter of a revolution, that is, in *one-fourth the time of any other engine* which expands to the original volume only in half a revolution, whereas the "*Differential*" *expands its charge to double volume in half the usual time, therefore, the expansion to the original volume is done in one quarter the time*, with the same speed of engine.

Hence the work is done with four times the rapidity, or the heat has only one quarter the time to flow away by the water jacket, thus effecting a very great saving, for the transmission of heat through metallic surfaces is directly proportional to the time that the difference of temperatures continues, as well as to the difference itself. In this way there is utilised nearly three-fourths of the heat formerly lost by that necessary evil, the water jacket. Moreover, a great amount of work is taken out of the ignited charge by expansion to twice the original volume, the temperature and pressure of the gases being reduced accordingly; whereas, with the Otto cycle, a whole cylinder full of products at high temperature and pressure were rejected by the exhaust, and all the heat in them lost. These two obvious sources of economy, combined with the simplicity of parts, are calculated to make the engine a complete success.

The wearing parts consist only of round pins or bearings and pistons. Calculation shows that there is not an attachment, the joint of which is subjected at any time to a pressure above 10 lb. Besides, the stress on the bearings increases gradually whilst compressing the charge, so that there is no sudden blow caused by the ignition and explosion of the charge, and at the moment of highest pressure on the pistons the short connecting rods (position in Fig. 28) are most favourably placed, being tangential to the pull, any angular thrust being taken up by the round bearings.

## TRIALS.

We have made some trials of a two horse-power (nominal) "Differential" gas engine, during a run of one hour, under ordinary working conditions; the engine had been running with the same load on for half an hour previously. The useful power was measured by a simple friction-brake consisting of a strap on the fly-wheel, with weights on one end and a spring balance attached to the other. The net weight was 41·4 lb., with a mean speed of 148 revolutions per minute, the effective circumference of the fly-wheel being 14 ft. This gives effective working $\frac{41 \cdot 4 \times 148 \times 14}{33{,}000} = 2 \cdot 6$ brake horse-power. The gas consumption during the hour, as indicated by a specially tested meter fixed close to the engine, was 67 cubic feet of London gas, that is, at the rate of $\frac{67}{2 \cdot 6}$ or 25·77 cubic feet per hour per brake horse-power.

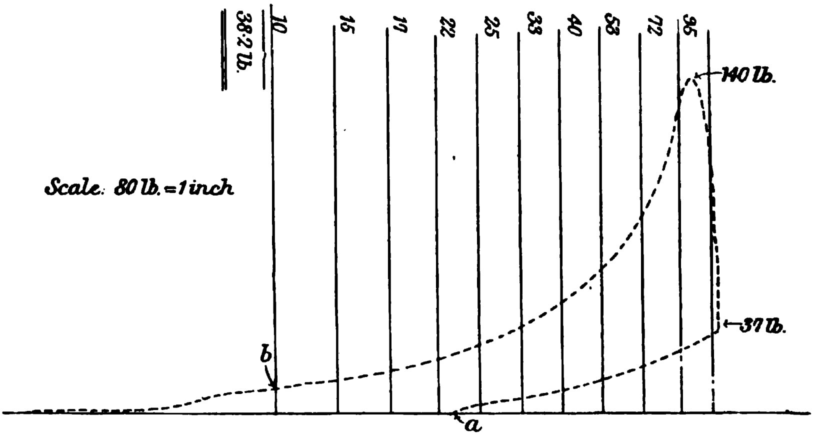
But this is not all, we have the particulars and figures obtained in other tests of the same engine with brake 2·94 horse-power, using 24·44 feet of gas per hour per brake horse-power; also another with 2·85 brake horse-power, and gas consumption 23·4 cubic feet per hour per brake horse-power. These are quite sufficient to establish the superior economy of the "Differential" engine; in fact, so far as we are aware, no 2 horse-power gas engine of any other type ever before did a brake horse-power with so small an amount of coal-gas of the same quality.

Mr. Atkinson had considerable hopes of improving on this, as the suction-port was not open long enough, and the exhaust-port did not open early enough.

### *Indicator Diagram.*

It is impossible to get a complete diagram from this engine, as no part of the cylinder is open to the space between the two pistons during a complete revolution. Fig. 30 is an indicator diagram taken from a 4 horse-power nominal.

FIG. 30.



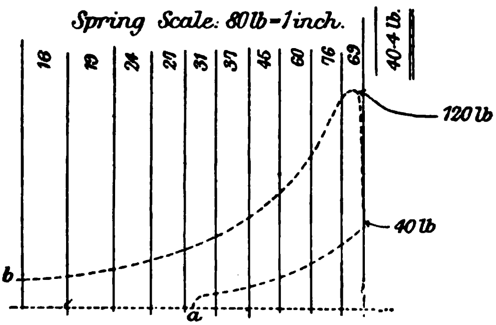
*Speed 140 revs per min. giving 6 indicated HP.*

DIAGRAM FROM ATKINSON'S DIFFERENTIAL ENGINE.

This is not a maximum diagram: it indicates 5 horse-power, taken when the engine was working very economically. The figure does not give the pressure during the whole of one revolution, as the port to the indicator is covered part of the time by one of the pistons. It opens at *a*, just after the suction has commenced, and closes at *b*, immediately before the exhaust is opened. This diagram is taken with the stroke of the working piston, and equal distances horizontally do not represent equal volumes between the pistons. The ordinates divide the diagram unequally, but into divisions which would represent equal volumes between the pistons.

Take another example, Fig. 31, which is the indicator-diagram from a 2 horse-power Differential Engine. To make this into an ordinary indicator-diagram, divide it into ten horizontal distances, which represent equal volumes between the two pistons. Erect ordinates at these points to cut the lines traced by the indicator pencil. Then, to get the true expansion curve, Fig. 32, divide a horizontal line into ten equal parts, erect ordinates, and mark off on these, heights corresponding to the pressure at each point on the diagram Fig. 31. At the point *b*, for instance, the pistons are travelling at the same speed, and the volume between them is neither increasing nor decreasing, consequently, supposing that no cooling is taking place, the line of pressure ought to be parallel to the atmospheric line. The curve in the diagram

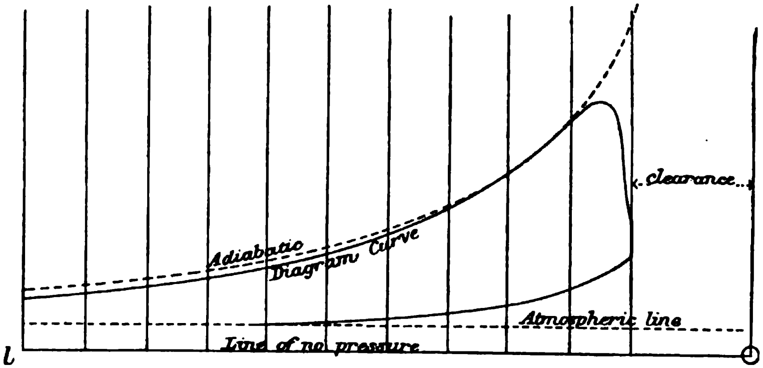
FIG. 31.



CARD FROM DIFFERENTIAL ENGINE.

Fig. 31, falls more rapidly than the true expansion-curve, Fig. 32, in the engine. It is evident from comparison with

FIG. 32.



the adiabatic-curve, that as regards sustained pressure this compares most favourably with the expansion curves usually obtained, and that of necessity with a homogeneous mixture.

The type of diagram can be varied in an engine by different conditions of strength of mixture, amount of compression, and time of ignition, &c., to that which experiment proves to be most suitable for economy and durability of the engine.

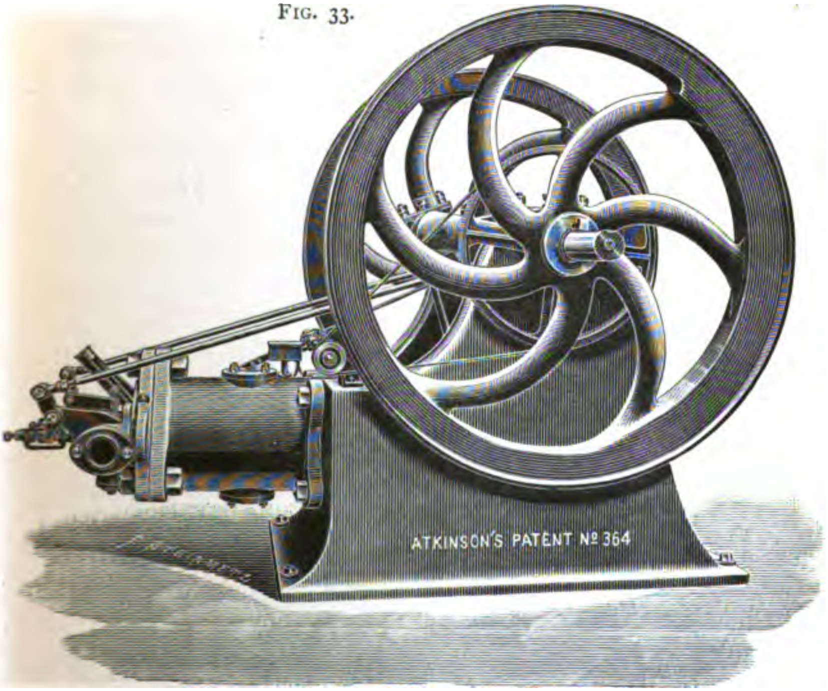
The richest mixture used consists of six parts of air to one of gas, but eight of air to one of ordinary coal gas is the usual strength. This mixture can be made to burn at lower pressure than the ordinary, in fact to give the same effect as Otto's diluted mixture, by simply varying the speed of engine and the point of ignition slightly, and this without residual products or any other diluent gases to retard combustion.

We recognise in this most ingenious invention of the "Differential" a great step in advance of all previous forms of internal combustion engine, towards the conditions most favourable to economy and efficiency in small gas motors. The regenerator *seems* impracticable for engines of small power with internal combustion. *Initial compression* has been proved to give good results. *Small surface exposure* of the cold cylinder walls, together with *rapid expansion,* very considerably reduce the amount of heat lost by conduction through the cylinder walls, so that it is compensated for by the prolonged combustion, which keeps the expansion curve up close to the adiabatic. Lastly, *long continued expansion,* to double initial volume of charge and down to or below atmospheric pressure, reduces the loss by the exhaust and converts a large proportion of the heat stored up in the gases into mechanical energy.

## THE ATKINSON "CYCLE" GAS ENGINE.

All the advantages of the Atkinson "Differential" are obtained with a single piston in the "Cycle" engine, Fig. 33,

FIG. 33.



**ATKINSON'S "CYCLE" GAS ENGINE.**

patent No. 3522, dated March 12, 1886, which is a most ingenious and interesting piece of mechanism designed by the same clever inventor. These two engines are exactly the same as regards (1) cycle of operations, (2) rapid rate of doing work, (3) great range of expansion, (4) great control by centres and novel yet simple and durable linkwork. The peculiarity of the **Cycle engine** is that a single piston performs a complete cycle of operations in the one cylinder during a single revolution of the crank shaft.

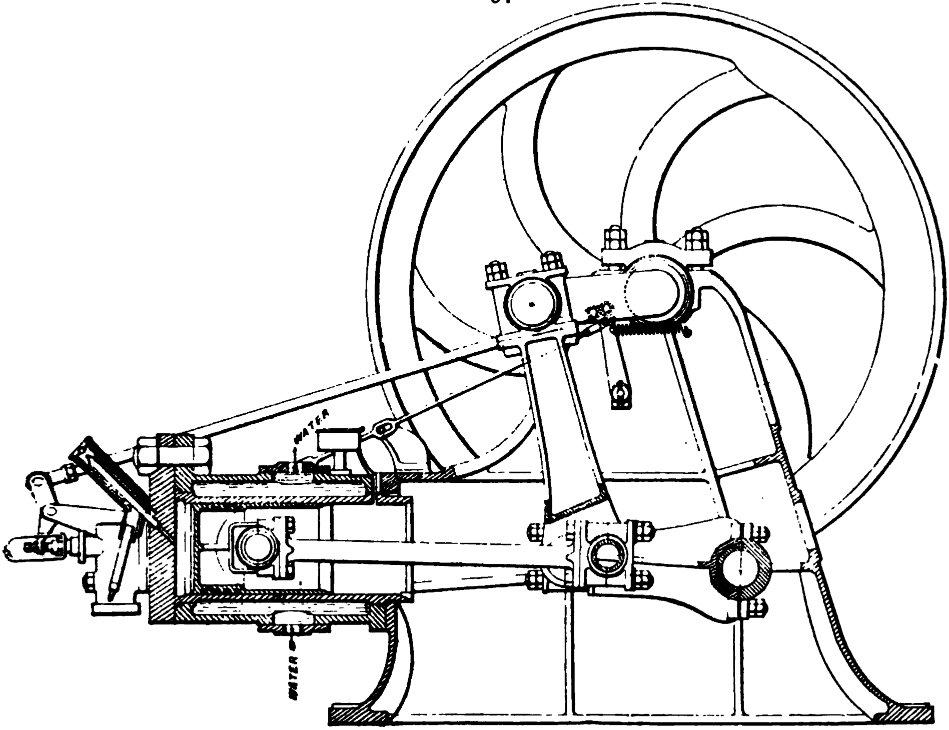
We have seen that in the Otto engine the cycle is only completed in two revolutions of the crank shaft, the one cylinder being used for the charging, compression, and expansion strokes. In order to have an impulse or working stroke every revolution it is common to employ a separate pump cylinder for mixing and compressing the charge before admitting it into the working cylinder. This secures greater regularity of speed, but necessarily increases the consumption of fuel per horse power, since the friction is increased, and the work done by the separate pump has to be deducted from that obtained in the working cylinder.

In some cases it is also considered most desirable from an economical point of view to clear out of the cylinder all the burnt products from previous combustions by a scavenger charge of air before introducing the *cool* explosive mixture; and some engines actually sacrifice a revolution for the purpose.

Such difficulties are overcome by Atkinson in the Cycle engine, which is of novel, peculiar, and simple design, realising exceptional economy and regularity of speed with perfectly satisfactory performance in practice.

The general arrangement of the Cycle engine is shown in Fig. 34. The connecting rod is not directly joined to the crank, but through a toggle link and rocking lever. The piston is fixed to the link at a point some distance from the toggle joint. Hence the initial explosion pressure on the piston does not come directly on the crank shaft, but is transmitted to the centre of this vibrating link, which has a large bearing lined with white metal across the base of the engine. Then the peculiar toggle motion gives a very uniform turning moment on the crank pin during the first four-fifths of the working stroke. The maximum pressure on the crank-pin and main bearings never exceeds 35 per cent. of the maximum initial pressure. This greatly reduces friction, wear and tear of the crank pin and main journals, and, in conjunction with the impulse every revolution, contributes to the remarkable regularity of speed of the engine running under widely varying loads. Thus, when the full load is suddenly thrown off there is only a very slight variation in speed, amounting

FIG. 34.



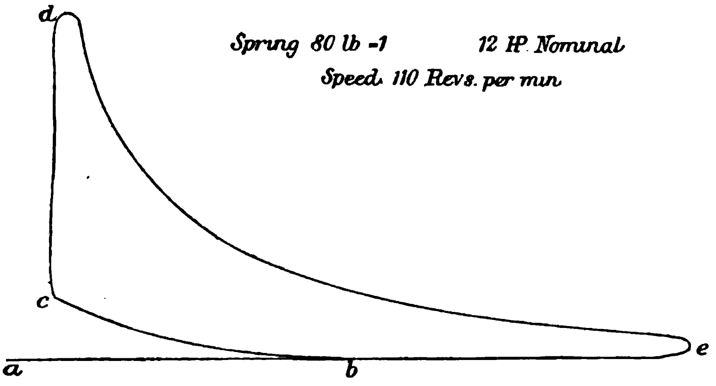
THE ATKINSON CYCLE GAS ENGINE (LONGITUDINAL SECTION).

to about 1·75 per cent. of the minimum speed at which the engine was running with full load.

By means of this linkwork the piston makes two double strokes, all of unequal length, for each revolution of the crank shaft. In a revolution of the crank shaft, starting from the extreme end of the cylinder, as in Fig. 34, the piston makes (1) a short forward stroke (6·3 inches), during which it draws in the charge of gas and air; (2) a shorter back stroke (5·03 inches), compressing the mixture; (3) the charge is then fired, and expands during a long forward working stroke (11·13 inches); and (4) a longer back stroke (12·43 inches), with exhaust open, which expels the whole of the products of combustion from the cylinder.

This cycle of operations can be readily followed on the indicator diagram, Fig. 35, which shows the pressure in the cylinder throughout *one* complete revolution, during which the piston starts at *a* and finally returns to the same position.

FIG. 35.



INDICATOR DIAGRAM FROM ATKINSON'S CYCLE GAS ENGINE.

(1) *a b*, *admission or suction* stroke;
(2) *b c*, *compression* stroke;
(3) *c d e*, ignition, *expansion* or *working* stroke;
(4) *e a*, *exhaust* stroke.

This great range of expansion utilizes more of the heat energy from a given quantity of gas, which is more thoroughly consumed, than if the burning mixture were only allowed to expand to its original volume at *b*. At the same time the terminal pressure in the cylinder is reduced to 10 or 14 lb., which gives a *quiet exhaust*. By reason of the rapid expansion, little heat is given to the water jacket. The gases retain the heat, which increases their pressure, and would be carried away by them in the exhaust were it not for the long continued expansion.

The exhaust valve is opened by a cam on the main shaft, as shown in Fig. 34; the cam rod works a lever which opens the valve inwards at end of cylinder. The suction valve is exactly similar, and is closed by a spring. There is only one other valve in the engine, i. e. the small gas-governor valve, which is opened by the suction-valve cam under the control of a sensitive governor. In fact the valve-gear is simple and easy to work.

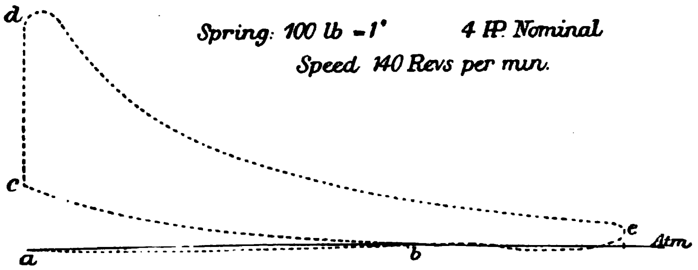
The *ignition* is effected by means of a small tube, closed at the top end and kept red hot by an external Bunsen burner, as shown in Fig. 34. There is no valve used to time the ignition. This is done simply by raising or lowering the chimney, so that, during compression, part of the charge is forced into the small tube, becomes ignited, and the flame passes into the cylinder as the piston has commenced its return stroke after compression. This requires adjustment to prevent the charge being fired too early before the end of the compression stroke. However, it must be borne in mind that considerable latitude is allowable as regards *time of ignition;* after turning the dead point, an early ignition gives high initial pressure followed by a lower expansion curve; on the other hand, a late ignition gives a lower initial pressure but higher expansion curve, notably so during the latter part of the working stroke. This mode of ignition, at once very simple and certain, also permits of high speeds of piston.

Thus it will be seen there is no slide valve in the engine; and there is the additional advantage that the gas and air passages are large and not liable to be blocked by oil or by products of combustion.

The intended thermo-dynamic cycle is performed without any mechanical disadvantages likely to affect the practical success of the engine. The friction is small, and extended trials prove that the engine runs quietly and steadily without any trouble or attention.

Not only does the peculiar construction of the mechanism secure high piston speed during working stroke with comparatively slow speed of crank shaft, but by adjusting the linkwork centres the builder is able to vary the compression and ratio of expansion to suit the quality of gas to be used and the speed of piston so as to give maximum efficiency.

FIG. 36.



INDICATOR DIAGRAM FROM ATKINSON'S CYCLE GAS ENGINE.

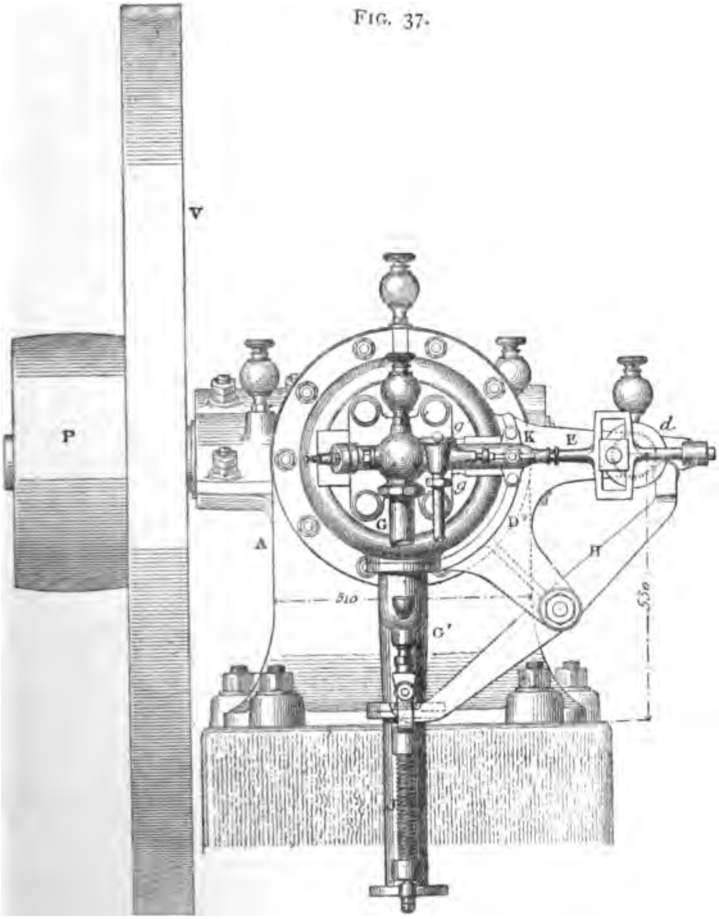
The diagram, Fig. 36, when compared with the preceding one, Fig. 35, shows this variation both as regards amount of compression and range of expansion. Only experience can determine the best conditions of working with different qualities of gas under certain circumstances.

Various kinds of cheap fuel gas, Dowson gas, and oil gas can be used with air as the fuel and working agent in the Cycle engine, giving uniform steadiness of power with exceptionally good economy in comparison with other heat engines in ordinary use. (See Chapter XVII. on Gas Motor Trials.)

## THE SIMPLEX MOTOR.

A good practical example of an engine having the cycle of working described by Beau de Rochas, is that made by Mr. Thomas Powell, of Rouen, and others, according to the patents taken out by Messrs. Edward Delamare-Deboutteville and Léon Malandin, in 1884.

FIG. 37.



END VIEW OF CYLINDER.

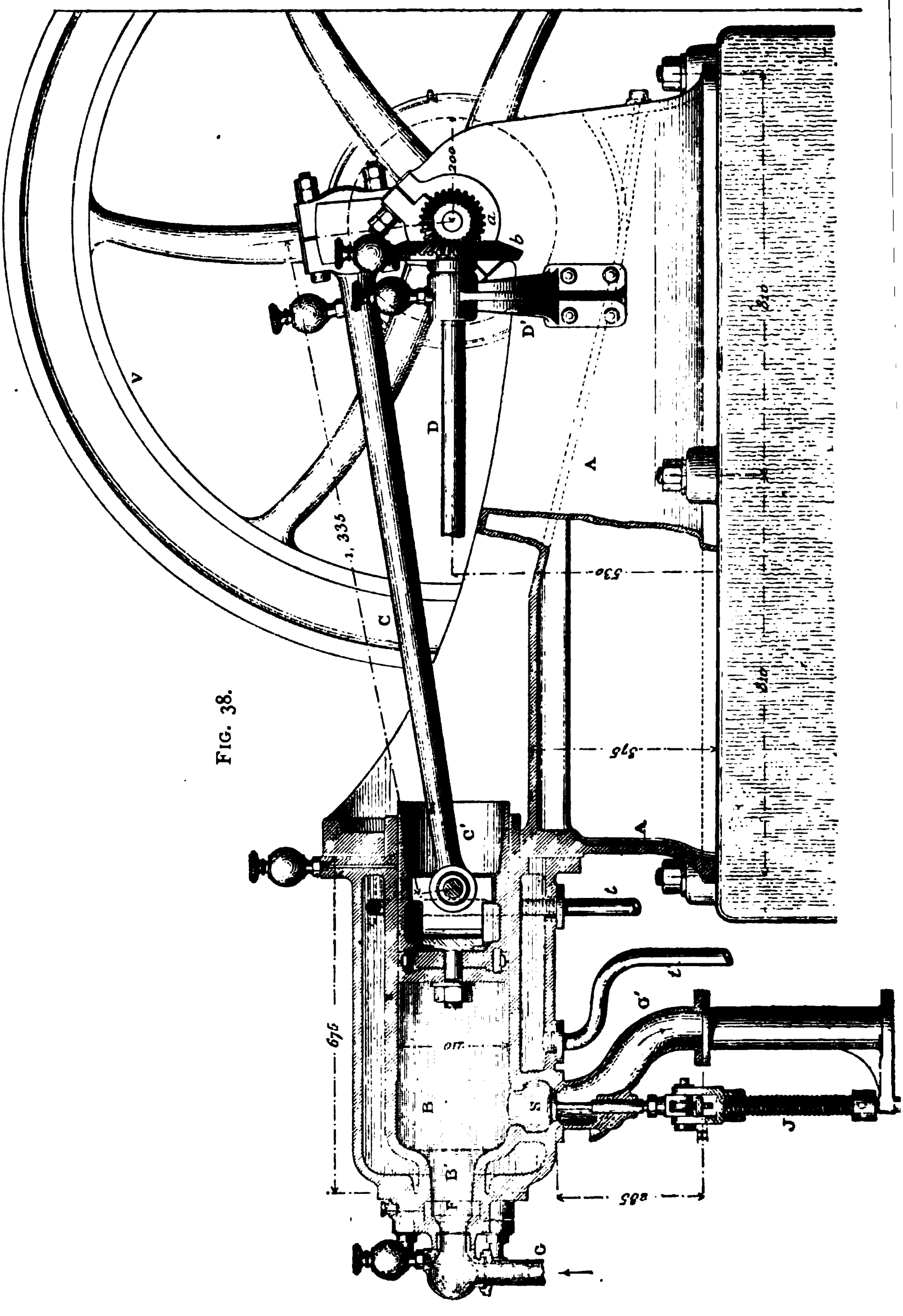


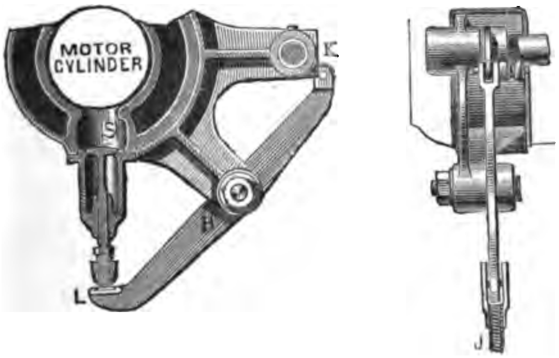
FIG. 38.

The SIMPLEX MOTOR, so called from the simplicity of its working parts and details as well as general action, is shown in elevation and longitudinal section of cylinder, Fig. 38, and end view of cylinder Fig. 37.

The working piston C′, Fig. 38, acts on the main shaft by the connecting-rod C in the usual way; V being the fly-wheel to regulate the motion. P is the driving pulley.

The side shaft D, driven by the bevel gear *a b* from the crank shaft, works the slide valve F by an eccentric, as well as the governor and exhaust valve H at the other end of the cylinder B. The strong spring J holds the mushroom valve S down on its seat until it is lifted by the lever H, actuated by cam K keyed upon the side shaft D. The drawings, Fig. 39, show the usual arrangement for opening the exhaust valve. One end of the lever H presses the spindle of the valve, and the other end carries a little roller. As the side-shaft D rotates, the projection or cam K keyed upon it, presses against the roller, lowers that end of the lever H, raising the other end L, which is thus enabled to overcome the spring J, and lift the valve until the cam has passed. When opened, the exhaust valve S allows the burnt products

FIG. 39.

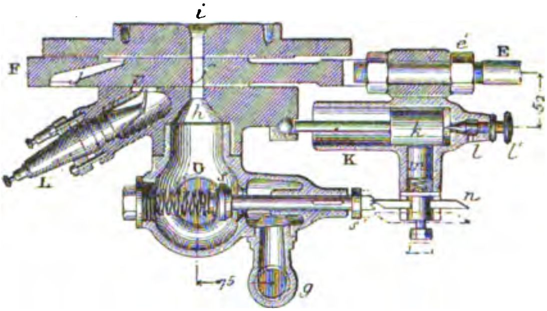


EXHAUST VALVE LEVER AND CAM.

to be driven out of the cylinder and away by the exhaust pipe G′, Figs. 37 and 38.

The water to cool the cylinder enters the jacket by the tube *t*′, Fig. 38, underneath the cylinder, and escapes by the pipe *t* at the top of cylinder. Gas from the pipe *g* is admitted when the valve *s* is raised by the knife-edge *n*, as in Fig. 40, and mixes with air entering by the pipe G, in the receptacle fixed on the slide cover.

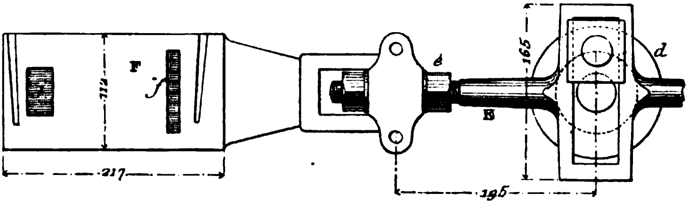
FIG. 40.



ADMISSION MECHANISM.

The gas and air are then violently sucked in through the conical channel *h*′ tapering to a rectangular passage, and thus, *thoroughly mixed*, go through the slide-valve port *f* and by *i* into the compression chamber B′, Fig. 38, at end of cylinder.

FIG. 41.

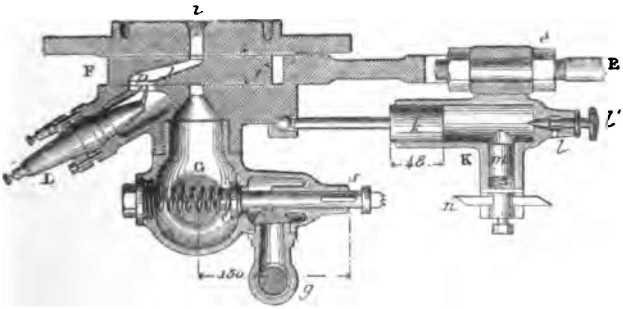


FRONT VIEW OF SLIDE VALVE.

The *slide valve* F is of simple construction, being merely a cast-iron plate pierced with two holes Fig. 41, the one *f* rectangular, for admission of the mixture, and the other opening *j* (Figs. 40 and 41) oblique with horizontal groove for ignition purposes.

*Ignition.*—A porcelain insulator L is placed in the cover plate, and in a small recess, Fig. 42, a continuous electric spark plays between the two platinum points *p* connected with the secondary circuit of an ordinary Ruhmkorff induction coil, the primary of which is excited by a bichromate of potash battery.

FIG. 42.

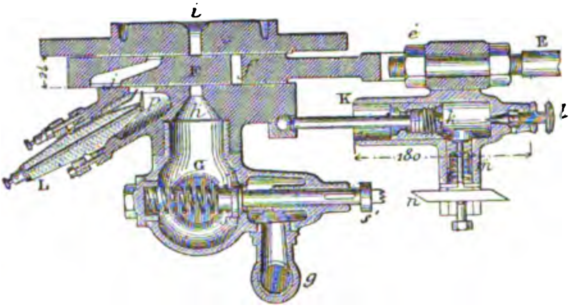


IGNITION OF COMPRESSED CHARGE.

As the edge of the oblique passage *j* in the slide F comes up to the admission port *i* of the cylinder, the compressed charge drives the burnt gases out of the combustion chamber by a small hole to the outer air, and in position Fig. 42 the fresh charge is ignited by the electric sparks which play continuously between the platinum points *p*. This expulsion of burnt products by the compressed mixture takes place in about $\frac{1}{150}$th of a second, and owing to the high igniting power of the spark, the compressed charge, even of poor gases, is fired with certainty and precision. By this arrangement, which facilitates lubrication, the slide is not much heated, and with ordinary attention will work a year without needing any repairs.

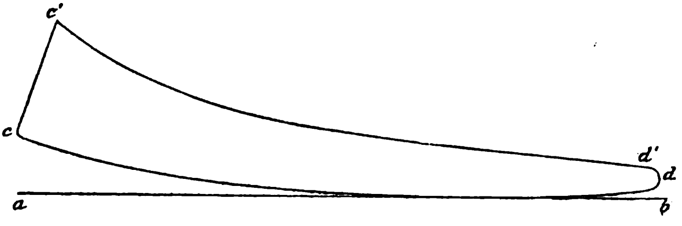
During *exhaust*, the slide valve and ports are as shown in Fig. 43, whilst the mushroom valve S is raised against the spring J, by the lever H, actuated by the cam K on the side shaft D, Figs. 37, 38 and 39.

FIG. 43.



EXPULSION OF BURNT PRODUCTS.

FIG. 44.



The *cycle* of the SIMPLEX motor can be readily followed by reference to the indicator diagram, Fig. 44.

*a*, *b*, *suction* or *charging* along atmospheric line.

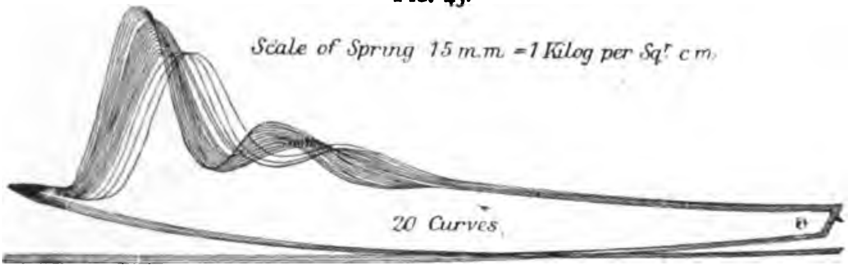
*b*, *c*, *compression* of charge.

*c c' d'*, *ignition* and *expansion* or working stroke.

*d a*, *exhaust* or *expulsion* of burnt products.

It is worthy of note that instead of having ignition at the dead point, as proposed by Beau de Rochas, in the Simplex motor this occurs somewhat later, as in Fig. 45, when the piston has already made part of its outward stroke.

FIG. 45.



INDICATOR DIAGRAM FROM SIMPLEX MOTOR.
Useful brake 5·68 Horse-power, Gas Consumption 750 litres, Speed 191 revs. per min.

Experience shows that there is a decided advantage, in delaying ignition under these conditions, both as regards increased effective power on the brake and greater steadiness of running, giving highest efficiency. In the first place, the bearings suffer less sudden shocks from the explosions, and less power is thus spent in distorting the bearings. This renders higher compression of the charges before ignition practicable; whilst the smaller space thus left between the cylinder cover and piston at the end of its stroke allows only a small quantity of burnt products to remain in the cylinder. In the second place, the work spent in over-compression is given back during the return of the piston, and the expansion pressure is better sustained throughout the stroke.

## Simplex Governors.

To regulate the speed of this engine the supply of gas is completely cut off during one or more admission strokes when the speed has become too high, until the normal speed is reached, and then the regular quantity of gas is again admitted.

The AIR-GOVERNOR, shown in Figs. 40, 42, and 43, consists of a pump barrel K, rigidly mounted on the slide at E, and moving to and fro with the slide. In this air-pump barrel there is a stationary piston *k*, whilst the piston-rod is fixed to the slide cover by two indiarubber washers, to allow of a slightly oblique motion. This air-pump communicates with the outer air by a small square hole *l*, which can be closed to any required degree by the micrometer screw *l'* with a conical point. Another small piston *m*, moves freely in a second cylinder fixed at right angles to K; this piston is pressed down by a spiral spring and the rod carries at its end a steel knife-edge *n*, which opens the valve *s* for admission of the gas when the small piston *m* is in position shown in Fig. 40.

By the micrometer screw *l'* the annular opening *l*, Figs. 40 and 42, around its conical point can be adjusted for any required normal speed of main shaft, 200 revolutions per minute say. Then the side shaft D, with slide F, will be driven at a speed of 100 revolutions per minute, and 100 cylinderfuls of air will be sucked through *l* into the large air-pump K in that space of time. The resulting air pressure does not overcome the spring in the small cylinder, and the piston *m* is not moved, whilst the knife-edge *n* on the piston-rod hits the stem *s'* and opens the gas admission valve *s* at each stroke, Fig. 40. Now, if from any cause the speed of the engine increases, more air will be sucked into K per minute, and the extra pressure thus produced will raise the small piston *m* and the knife-edge *n*, so as to miss the gas valve stem *s'*, as shown in dotted lines. No gas being admitted, the engine will miss fire, and no impulse will be given to the motor piston until the speed slows down to the normal.

This *air-governor* is specially suitable for gas engines on board ship, or for locomotives, because it is independent of level, and works equally well in any position.

For stationary engines, this arrangement has been replaced in the Simplex motor by the PENDULUM GOVERNOR, which

$T = \pi \sqrt{l/g}$

is both simpler and cheaper. This governor is based on the principle that the time of vibration of a simple pendulum at any place depends only on the length of the pendulum. It is, in fact, a compound pendulum, composed of two masses fixed on a rod, with a pivot in the middle carried on a bearing rigidly fixed to the slide cover, Fig. 46. The heavier mass, of cylindrical form, is fixed on the lower part of the stem, and the lighter spherical mass above the bearing can be adjusted by screw and locknuts. This pendulum falls freely by its own weight, so that the *time* taken in falling is always the same for any given length of stem; and the upper mass is adjusted to make the engine run at any required speed.

FIG. 46.

$T \propto \sqrt{l}$

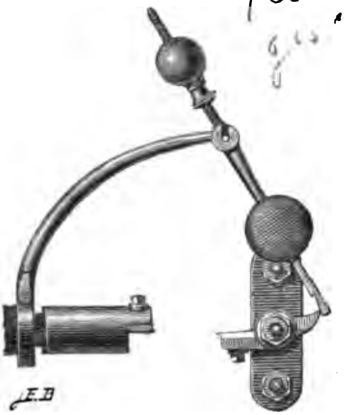
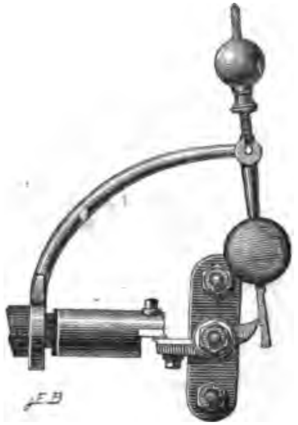


FIG. 47.



PENDULUM GOVERNOR.

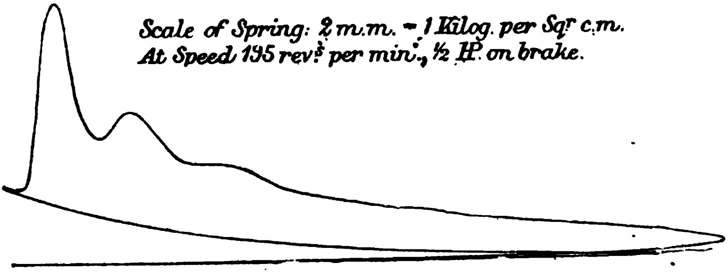
Fixed to the slide-valve F of the motor, and moving to and fro with it, is a stem carrying a frame with two knife-edges, one of which comes against the stem *s'* of the admission valve *s* and opens it, whilst the other smaller knife-edge is engaged with the notch in the steel end of the pendulum, holding the swing-frame in the horizontal position. Otherwise the larger and heavier knife-edge, with a spring, tends to make the frame swing below and fail to open the gas valve as in Fig. 47. This will take place whenever a slightly accelerated speed of slide valve brings the swing-frame back so quickly that the small knife-edge will miss the notch of the pendulum, which has taken the same time to fall as before.

In this way the gas admission valve is left closed and the gas supply cut off, no explosive mixture being formed, and the engine will slow down to its normal speed for want of the usual impulse.

Then the ordinary action of this governor is as follows:—During the back stroke of the slide the small knife-edge engages the notch of the pendulum, which is urged into its highest position. When the slide makes its forward stroke, the small knife-edge being in gear with the notch, the pendulum in its fall brings the swing-frame into the horizontal position, the large knife-edge hits the gas valve, opens it to admit the gas, and the explosive mixture is formed.

The small knife-edge and notch hit or miss according to the speed of the engine or slide-valve, since the time of fall of the pendulum is always the same.

FIG. 48.

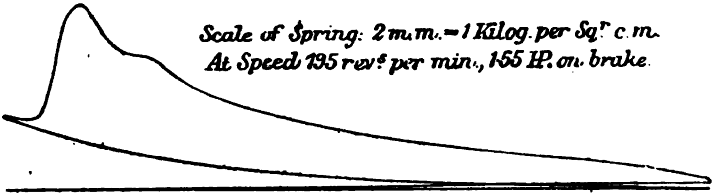


INDICATOR DIAGRAM FROM SIMPLEX MOTOR (HALF LOAD).

The indicator diagrams, Figs. 48 and 49, taken from a small 1 H.P. engine when running with half load and full load, show some interesting results of this mode of governing.

The explosion curve, Fig. 48, indicates a higher initial pressure than in Fig. 49 with full load. This is always the case, and the explanation is obvious. When the engine is running light, the governor cuts off the supply of gas, and there are frequent miss-fires, only atmospheric air being drawn in ; the burnt products from previous combustions are thus in great part swept out, and the cylinder cooled, so that when gas is admitted, the mixture being richer, cooler, and undiluted, gives a more violent explosion than usual.

FIG. 49.



INDICATOR DIAGRAM FROM SIMPLEX MOTOR (FULL LOAD.)

## Simplex Starting Gear.

The first and readiest method of starting *small* gas engines is to *give the fly-wheel a few turns by hand*, so as to draw a charge of explosive mixture into the cylinder, compress and fire it, until an explosion or two gets up speed and stores sufficient energy in the fly-wheel to carry the engine through a complete cycle.

For larger engines with heavy fly-wheels several men are needed to give the first few turns. With engines above 20 H.P. the operation is tedious, troublesome, and dangerous ; in fact some handy automatic method of starting becomes absolutely necessary in the long run.

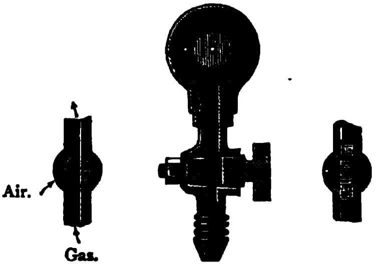
We have already seen that *storage of the burnt gases* *under pressure in a separate receiver* is found unsatisfactory in practice, owing to leakage of the valves and cooling, so that the gases could not be kept for any considerable period of time under sufficient pressure to start the engine when wanted.

Another plan was *to store up an explosive mixture of gas and air in a reservoir* at a pressure of about 60 lb. per sq. in. above atmosphere, taken from the compression cylinder while the engine was running, to start it next time. Besides the trouble of leakage and loss of pressure, this device involved the risk of accidental explosions, sometimes so violent as to burst the vessel containing the explosive mixture. Hence both experience and prudence dictated that this plan ought to be abandoned.

Others, again, use a *small special gas motor, of very simple construction*, to start a large engine of about 100 H.P., acting directly on the fly-wheels by friction gear.

A simple and effective method of starting has been devised by the inventors of the Simplex motor. It is only necessary to fit on the igniting apparatus a three-way cock with a small gas pipe or piece of indiarubber from the gas supply of the engine. This three-way cock, shown in plan, section and elevation in Fig. 50, has a small oblique hole at its side by which air enters to mix with the gas sucked in

FIG. 50.

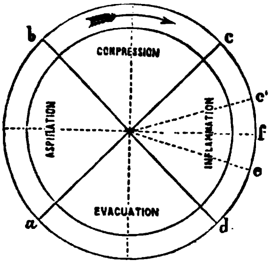


PLAN. SECTION. ELEVATION.

through the central opening, before reaching the slide valve port on its way to the cylinder.

In the cycle diagram, Fig. 51, *c* represents the dead point before the ignition or inflammation part of the cycle.

FIG. 51.



Engines up to 25 H.P. are started from the ignition point *c* as follows. The spark between the platinum points is stopped by the contact-breaker of the induction coil. The three-way cock is opened, and the gas supply cock set to the marked position. The fly-wheel is slowly turned to draw the explosive mixture into the compression chamber in the cylinder, until the point *e* is reached, when the piston has made about two-thirds of its stroke. Now the three-way cock is closed and the main gas cock of the engine set at the position for starting.

The fly-wheel is turned backwards from *e* to *e'*, to compress the charge a little. The electric current is switched on, and sparks play between the platinum points, igniting the charge, and the explosion gives the piston and fly-wheel an impulse sufficient to carry them past the dead points and so start the engine.

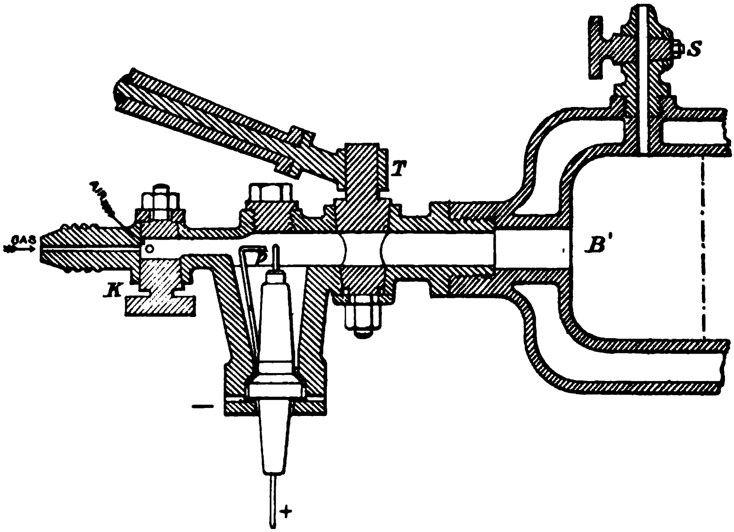
Larger engines, of 50 or 100 H.P., are started with greater ease, without the usual manual labour, by another very simple process.

In the engine cylinder, above the compression chamber a hole is tapped, such as is needed for an indicator, and supplied with a small stop cock S, Fig. 52.

The engine must be stopped, not at the ignition point, as before, but somewhat in advance, at the point *f*, Fig. 51, with the crank at an angle of 90°, when the piston has made about half its outward stroke. This can easily be done by means of the three-way cock.

Now, to start the engine. Open the cock S at top of the cylinder, and the three-way cock with the gas cock to the marked position. The gas under slight pressure enters the cylinder, drawing in air with it through the small oblique hole in the three-way cock. This explosive mixture drives the burnt products out of the cylinder by the cock S, and fills the space behind the piston. When the cylinder is full of the explosive charge, close the cock S on top of cylinder, and the three-way cock. Set the main gas cock at the starting position, switch on the electric current to pass the electric spark between the points *p*, and ignite the charge. The energy of the explosion is sufficient to start the largest engines.

FIG. 52.



SIMPLEX SELF-STARTER.

A similar plan of starting may also be applied to gas engines of this type having different ignition arrangements. This may be done by screwing the self-starting gear on one side of the compression chamber B′, as shown in Fig. 52. K is the three-way cock, to which is attached an indiarubber tube from the gas supply. Open the gas tap T, turn the fly-wheel to draw in an explosive mixture of gas and air; then close K, pass an electric spark between the platinum points *p* to fire the charge and drive the piston forward. When the engine is thus started, the tap T is closed and the ordinary method of ignition used.

The Simplex engine runs with remarkable ease and steadiness. It is found in practice that great regularity of speed, for electric lighting purposes, is obtained by driving the dynamo directly from the engine with a short belt and having the fly-wheel as close as possible to the pulley of the dynamo. Although there may be slight waste of power due to slipping, yet, with a proper belt, the loss is less than that due to counter shafts and bearings.

In the Paris Exhibition, 1889, a Simplex engine, Fig. 53, of 100 actual horse-power, the largest single-cylinder gas engine ever made, was working at the Quai d'Orsay with Dowson gas.

The cylinder is 22·64 inches in diameter, and the stroke 37·4 inches. The crank shaft bearings are long and strong.* A pendulum governor (page 63) keeps the speed about 107 revolutions per minute. The compressed charge is ignited when the crank has turned through an angle of 15 degrees after the piston has commenced its working stroke. The exhaust valve is opened by a cam on the side shaft working a long lever with shifting fulcrum, and called the *crocodile's jaw*. The gases are rejected through a large exhaust pipe into a silencing chamber filled with flints and pebbles.

The gas to supply the engine is made by a Dowson producer, much too small for the purpose, and this is kept

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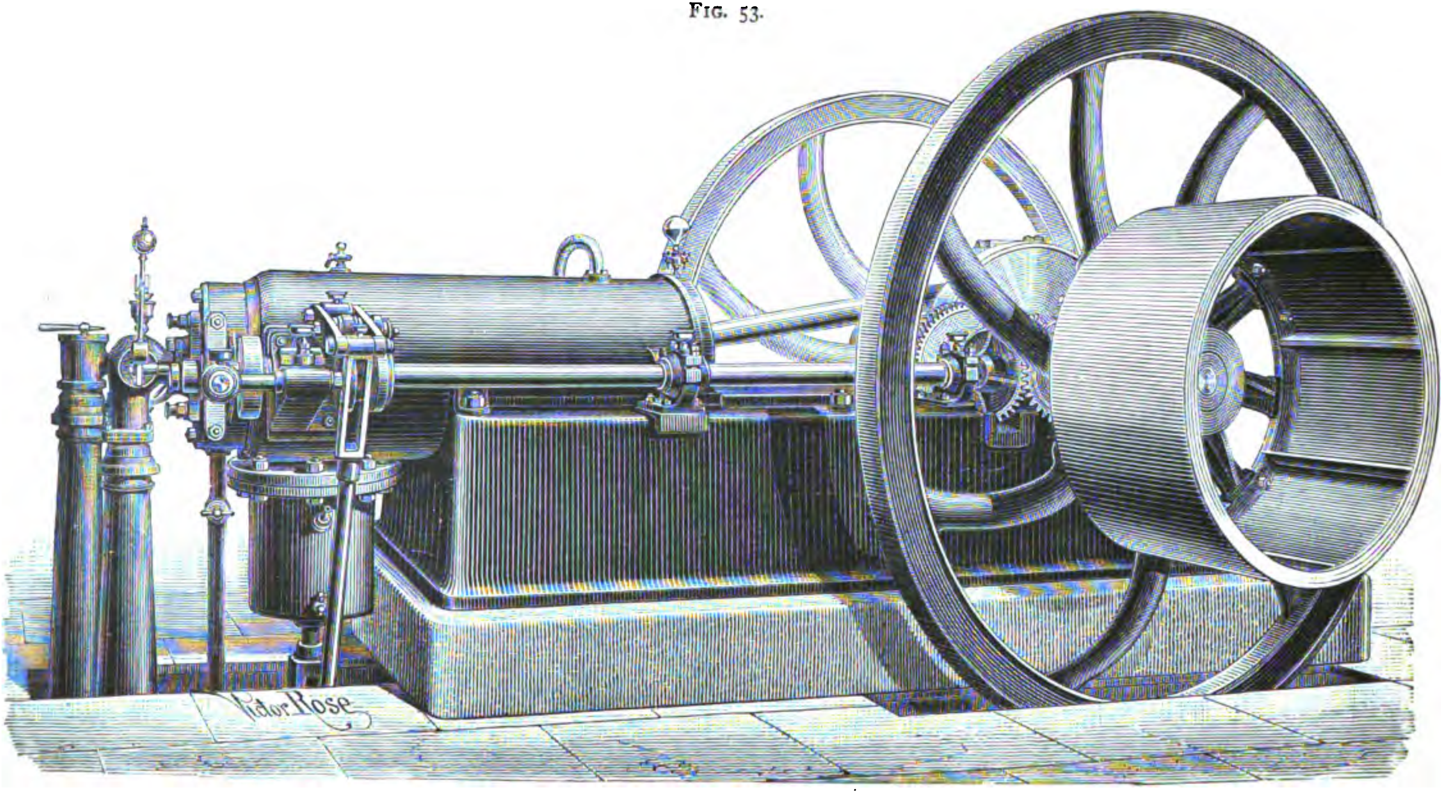
* For drawings of this engine see 'Engineering,' September 27, 1889.

FIG. 53.



SIMPLEX GAS ENGINE (100 H.P.).

alight all night, although the engine is only required to run 5 hours a day at about 60 H.P. Under these unfavourable circumstances the total

### Fuel Consumption,

including both night and day, is 150 kilograms (330 lb.) of garnant anthracite, or 175 kilog. of a cheaper coal of inferior quality. In order to test the consumption without any load, the engine was run light one day, and 125 kilog. of coal consumed by the producer during the night and day. These results show that for continuous working at full power, that is, from 80 to 100 H.P., an extremely low consumption, less than 1 lb. of coal per hour per horse-power, may reasonably be expected.

Trials made in 1885 by Dr. Witz show that a Simplex engine gave 6·7 H.P. on the brake with a consumption of ordinary coal gas at the rate of 22 cubic feet per hour per brake H.P., whilst with Dowson gas this engine actually converted 20 per cent. of the total available heat of combustion into work.

Apart from special experiments, the daily records from these engines in practice give the following highly satisfactory results:—A 16 H.P. engine, driven by coal gas and giving out 12 H.P. effective, uses 2327 cubic feet per day of 10 hours, or 19·4 cubic feet per hour per brake H.P. Another engine, with Dowson generator, giving 15 H.P., consumes only 1¼ lb. of coal per hour per brake H.P. This combination of Dowson gas generator with a 50 H.P. engine, requires, on an average for ordinary working, coal at the rate of about 1 lb. per hour per brake horse-power.

# CHAPTER IV.

## USES OF PETROLEUM IN PRIME MOTORS.

### Carburetted Air.

AT the ordinary temperature, atmospheric air, when passed through and over gasoline or volatile petroleum spirit of low specific gravity 0·650 to 0·700, liberates some of the gasoline, and the air thus saturated with petroleum vapour is equal in heating or lighting power to ordinary coal gas. Since this inflammable vapour is given off at the ordinary temperature, gasoline is very dangerous and explosive.

The process of *carburetting air* varies very much, and many contrivances have been devised to carry it out. In America the apparatus usually consists of an air-pump in the cellar of a house, to force cool air through a pipe into the *carburator* or gas generator containing the gasoline, fixed underground at a safe distance from the house. Another pipe conveys the carburetted air to the house or place where it is burned.

To facilitate evaporation it is desirable to have large surfaces of contact between the air and volatile liquid. This is done in several ways, such as agitating the petroleum and forming fine spray by paddles or other means whilst forcing the air through it.

Such methods of carburetting air are not without their drawbacks. The more volatile constituents of the petroleum pass off first with the air, and the remaining liquid is of increased density. Moreover, heat is absorbed in evaporation. This gradually cools the liquid, and leaves it in a less favourable condition to give off vapour and saturate the air, until at last the thick oily residue left after evaporation has often to be thrown away as useless. Some of the organic and mineral substances in the oil are also taken up by the air, and form troublesome deposits and incrustations when burned in the engine cylinder.

With gasoline at 9*d.* per gallon, the cost of the manufacture of gas is about 3*s.* 4*d.* per 1000 cubic feet. This is largely used in districts where the oil is cheap and plentiful.

Steam under pressure is often used along with air to draw or force oil in the finely-divided condition as spray into furnaces where it is burned.

Messrs. Delamare-Deboutteville and Malandin, of Rouen, employ a CARBURATOR in conjunction with small powers as from 1 H.P. to 8 H.P. of their Simplex motor, in isolated installations and country places where gas is not available and the duty on petroleum is not so heavy as to prohibit its use as a source of power.

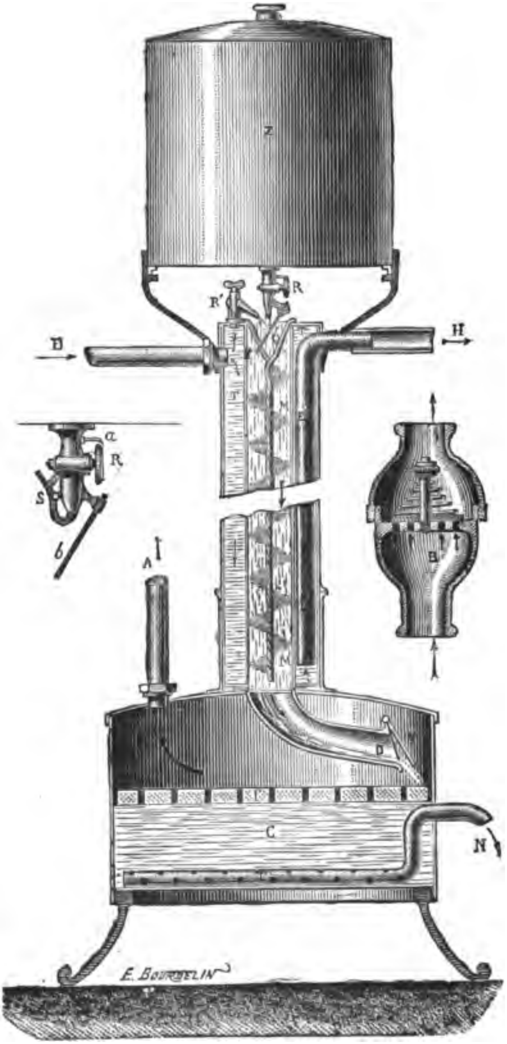
The *carburator*, Fig. 54, is simple and inexpensive. It consists of an oil-tank Z, from which a thin stream of oil flows by the stop-cock R furnished with a graduated disk. The flow is regulated by an equilibrium valve S, which presses gently against the opening, and stops it when the admission of gas to the engine cylinder is interrupted by the governor. The hot water in the space T comes from the cooling-jacket of the motor cylinder by the pipe E. On leaving the motor the water is at 60° or 70° C., but on reaching the carburator its temperature is generally 40° or 50° C. (122° Fahr.). This water heats the chamber M and aids evaporation.

Before starting the engine, water is allowed to flow into the carburator by R′, until it escapes by the overflow pipe N. Then the stop-cock R′, is closed and R opened, to allow the oil to fall into M, over the spiral horse-hair brush, at the rate of 1 litre per hour for the 1 H.P. engine. The valve D allows the mixture of liquid and spirit vapour to flow into the closed vessel V, whence the gaseous part passes, by the pipe A and through the safety-valve B, directly to the motor cylinder.

When the water-jacket has reached a temperature of 30°

or 40° C., the cock R′ is opened, and a stream of hot water flows from the motor. This hot water and the volatile oil

FIG. 54.



THE SIMPLEX CARBURATOR.

fall together into M, on the spiral horse-hair brush, and thus intimately mixed, the complete evaporation of the petroleum spirit is effected by heating and exposure of large surface.

A perforated cork disk F floats on the water C, to lessen the effects of the sudden suction of the motor piston, allowing vapour and not spray to pass into the cylinder. The overflow water is completely rejected by N, and takes with it all the mineral and vegetable constituents of the oil, but only an insignificant quantity of the volatile petroleum spirit. In this way the constituents likely to form a deposit or incrustation in the cylinder are absorbed and taken away by the water, and the engine is found to be clean and free from deposit after working several months with this petroleum vapour.

Gasoline of density ·650 to ·700 is used, at a cost of about half a franc, that is to say, 4·75*d.* per litre.

There is, of course, no comparison to be made between the cost of working the Simplex motor with this carburetted air and with cheap fuel gas, which is employed in motors above 6 H.P., giving much greater economy.

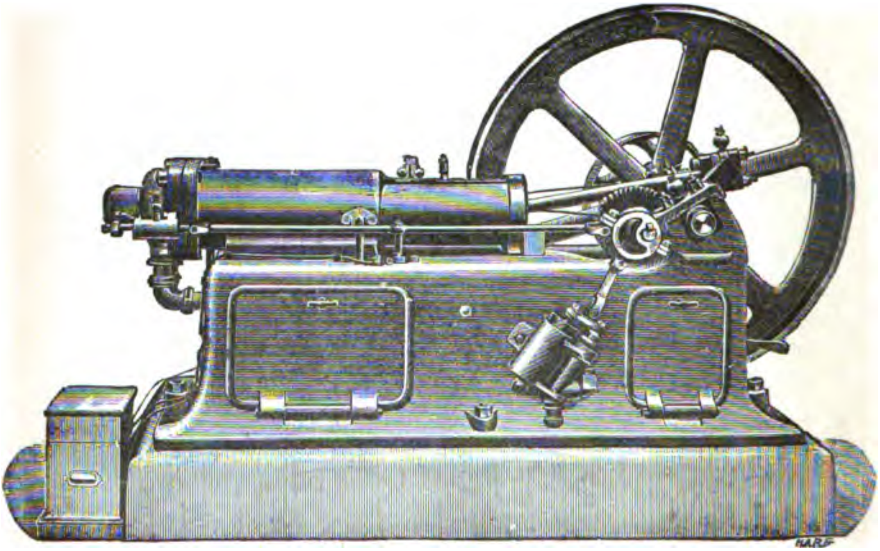
## Common Petroleum Oil Engine.

The great disadvantages hitherto attending the use of petroleum as a source of power in the internal combustion engine, have been mainly due to the low flashing point, highly inflammable and dangerous nature of the lighter products of the distillation of petroleum, such as benzine, petroleum spirit, and gasoline, which were most suitable for the purpose. The danger and difficulty in procuring, storing, and using this volatile spirit prohibited its general adoption.

The novel and important feature of the new prime motor of 1888, the PRIESTMAN OIL ENGINE, is the use of the ***common petroleum oil of commerce*** (kerosene, or lamp oil), ***at once as fuel and working agent.***

The engine shown in Fig. 55 is remarkably self-contained. The oil supply necessary for a run of a day or two is kept in a closed iron tank or reservoir in the foundation of the engine at the door seen to the right. A small counter shaft, geared with a pair of pinions from the main shaft, drives the air and water pumps, attached to the framework. The water necessary to cool the engine cylinder is contained in a cistern formed in the foundation of the engine, and is kept in circulation by the small pump alongside. This device dispenses with the separate water tank and piping, at least for engines of small power.

FIG. 55.



THE PRIESTMAN OIL ENGINE.

The air pump forces air into the petroleum supply reservoir at a pressure from 5 to 15 lb. per square inch, according to the size of the engine. This is necessary in order to obtain a stream of oil, which is allowed to mix with another portion of air brought through a separate passage into the *vaporizer* enclosed inside the framing below the engine cylinder at the door to the left Fig. 55. The oil thus forced from the reservoir mixes with the compressed air, forming vapour, which is injected through a nozzle into the spray chamber with a special device for regulating the supply of oil and air. A centrifugal governor, driven directly from the crank shaft, regulates the proportion of mixture for the work required to be done by the engine.

*The mixture of spray and air is heated by the hot products of combustion, on their way round this vaporizer, before being allowed to escape by the exhaust.* The vaporizer is in direct communication with the end of the cylinder; and the charge, thoroughly mixed and converted into vapour, is drawn through an automatic suction valve into the cylinder by the piston in its forward stroke. (See page 402.)

During the previous backstroke of piston, the exhaust valve had been pressed and opened by means of a lever moved by the side shaft, so that the burnt gases were ejected to heat the incoming charge.

Then, after the return compression stroke of the piston, the side shaft completes an electric circuit, causing an electric spark from an induction coil to play between two well-insulated wires inside the cylinder, and the charge is ignited. The combustion is so complete that little or no deposit of carbon is to be found in the cylinder, and the *petroleum* at the same time *lubricates the piston and cylinder.* During the return stroke the products of combustion are ejected, thus making the cycle of operations exactly the same as in the Otto engine cylinder.

Ignition and combustion take place with certainty and regularity, partly owing to the highly inflammable nature of the mixture, as well as to careful attention to details, such as having broad surface terminals and good porcelain insulators on the wires, which need only to be occasionally cleaned.

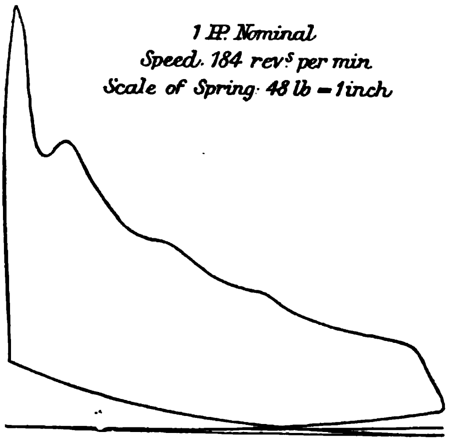
Both the contact maker of electric circuit and the exhaust valve lever are worked by the horizontal side shaft, driven from the same crank as the air and water pumps. So many separate functions being thus performed by this one shaft, reduces the working parts and simplifies the engine.

The two main valves are simple T-shaped mushrooms, held against their seats by spiral springs, and *opening inwards* to the cylinder—the exhaust valve when pressed by the lever, and the admission valve being drawn in by the piston diminishing the pressure on that side of it during the forward stroke.

There are thus few working parts in the engine liable to get out of order.

*To start the engine*, the vaporizer is heated to the required temperature by a small oil lamp in a few minutes, a few strokes are then given to the pump by hand to force a small quantity of oil vapour into the vaporizer and cylinder; then the fly-wheel requires a turn or two until combustion takes place and the engine continues to run steadily. No further attention is necessary, as the *exhaust products heat the vaporizer* and the pumps are worked automatically.

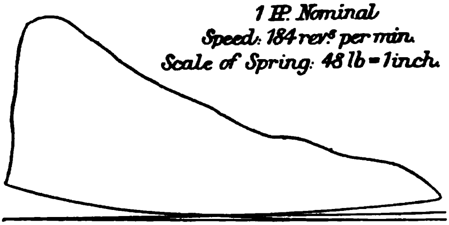
FIG. 56.



INDICATOR DIAGRAM,
PRIESTMAN OIL ENGINE WITH FULL LOAD.

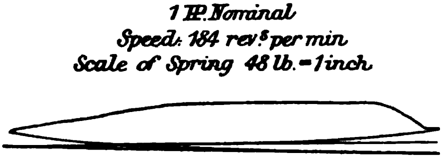
In order to secure regularity and steadiness in running with any variation of load, instead of completely cutting off the supply of vapour, and thus missing explosions, the *Priestman oil engine is governed by reducing the charge of vapour* admitted into the cylinder when the engine is running with less than its full load; and the governor thus regulates the intensity of the explosion according to the amount of work to be done. The diagrams, Figs. 56, 57, 58, show this very clearly for a small 1 H.P. engine, and Figs. 59 and 60 for another engine giving 12 H.P. on the brake.

FIG. 57.



INDICATOR DIAGRAM,
PRIESTMAN OIL ENGINE WITH HALF LOAD.

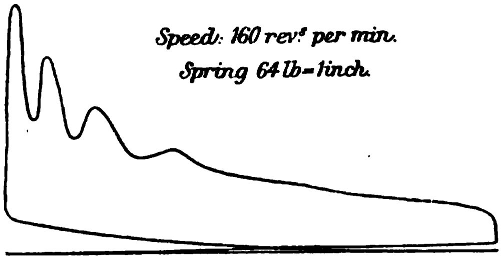
FIG. 58.



INDICATOR DIAGRAM,
PRIESTMAN OIL ENGINE RUNNING WITHOUT LOAD.

The combustion takes place quietly and regularly, whether the engine is running light or with full load. Hence the engine is admirably adapted for small isolated electric light installations, and for motive power in many places without a gas supply, or where it is too expensive, in this country as well as in America and Australia.

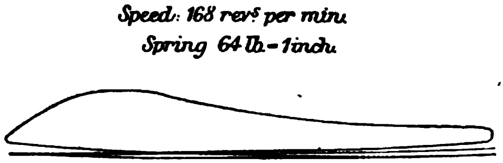
FIG. 59.



INDICATOR DIAGRAM,
PRIESTMAN OIL ENGINE RUNNING WITH LOAD.

This engine can readily supply motive power, not only from common petroleum oils of specific gravity ·800 and flashing point 100° F., but also from heavy Scotch paraffin of specific gravity ·820 and flashing point about 150° F. Even common creosote oil has been successfully used, and Fig. 61 is an indicator diagram taken from a Priestman oil engine working with creosote oil and giving 24 actual horse-power on the brake; but, from the dirty nature of this material, its use is not recommended.

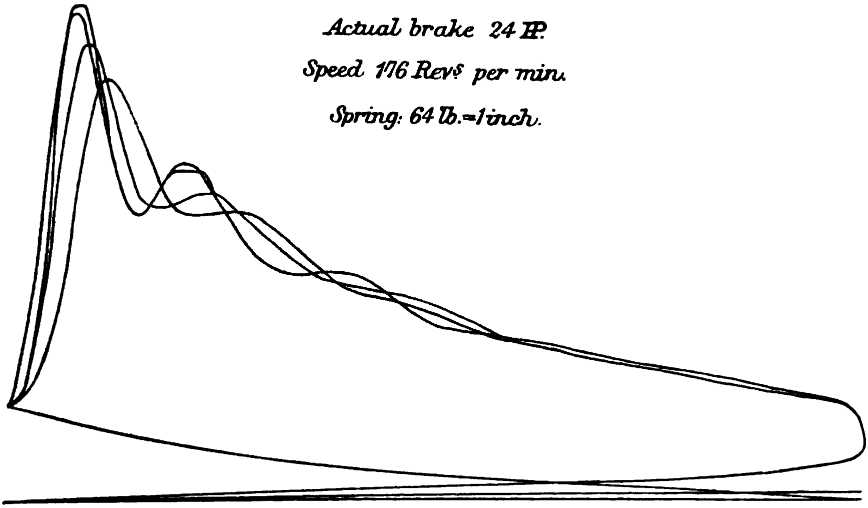
FIG. 60.



INDICATOR DIAGRAM,
PRIESTMAN OIL ENGINE RUNNING WITHOUT LOAD.

The engine works best with ordinary petroleum oil having a specific gravity of about ·802, and the consumption is at the rate of about 1·2 pint per actual horse-power per hour with full load. With this oil the working parts require very much less frequent cleaning than with heavy creosote oil.

FIG. 61.



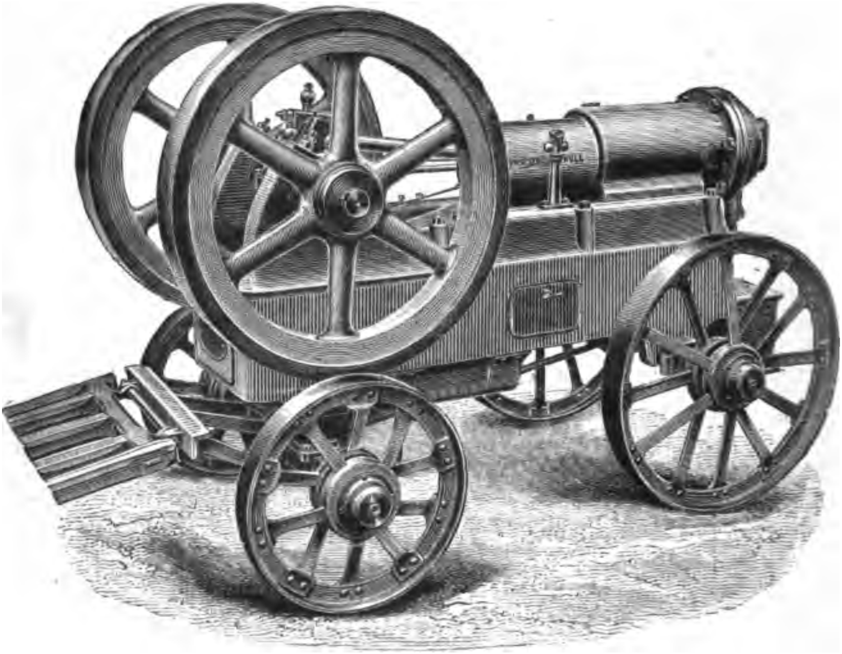
INDICATOR DIAGRAMS FROM THE PRIESTMAN ENGINE WORKED WITH CREOSOTE OIL.

Such a prime motor, compact and self-contained, is very convenient in small powers for many industrial processes, agricultural work, in lighthouses, and even in tea-plantations, where coal or coal gas is more expensive than oil. Moreover, petroleum can be easily stowed in tanks or holds in the bottom of boats, and possesses, for the same bulk, a greater store of energy than coal, so that this common petroleum engine is suitable for work on board ship. However, experience alone can decide the economy to be effected in this direction. The Priestman has been used for pumping at collieries.

This motor, mounted on wheels, possesses many advantages as a portable oil-engine fit for farm use.

Fig. 62 represents the first 6 horse-power portable petroleum engine, introduced and exhibited at the Jubilee Meeting of the Royal Agricultural Society, in 1889, and which was awarded the Society's Silver Medal. It requires but little attention, and will doubtless be of great service to farmers. It is self-contained, having oil-cistern, water-tank, pumps, vaporizer, and firing apparatus. Its fuel—ordinary paraffin oil—can be had almost everywhere.

FIG. 62.



PRIESTMAN PORTABLE OIL ENGINE.

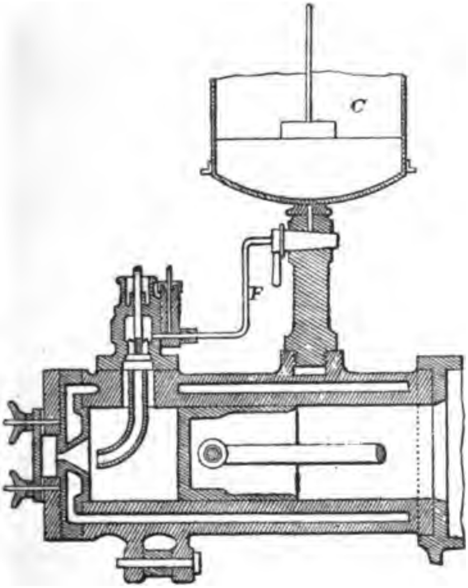
Thus we have in the Priestman Oil Engine a good practical method of using ordinary mineral oils, as the refined petroleum oil of commerce, specific gravity ·800, to produce power with *perfect safety in the hands of the general public.* The oil is always well mixed with air and thoroughly vaporised before entering the cylinder, in order to secure complete combustion under working conditions. Creosote and the heavy oils of specific gravity ·820, having high flashing point, are likely to leave a larger deposit of unburnt carbon in the cylinder.

In fact, experience shows that more complete combustion, and greater power, is obtained from the volatile spirit than from the oil itself, but at the same time the danger of explosion is incurred with the highly inflammable spirit of low flashing point.

## Spiel's Engine.

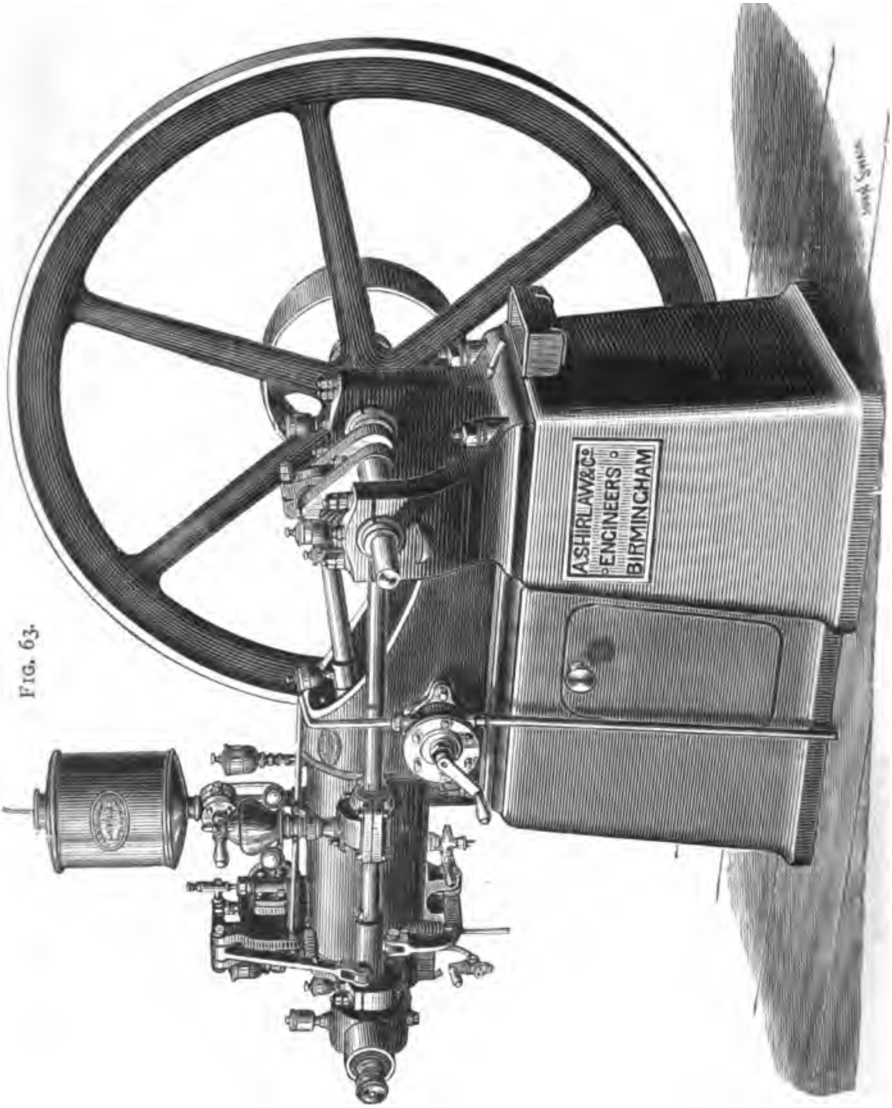
SPIEL'S ENGINE, Fig. 63, as made by Messrs. Shirlaw and Co., is a form of internal combustion engine which uses liquid petroleum spirit, benzoline, benzine, naphtha, or shale spirit of specific gravity ·700 to ·730. Only these

FIG. 64.



LONGITUDINAL SECTION.

FIG. 63.



SPIEL'S ENGINE.

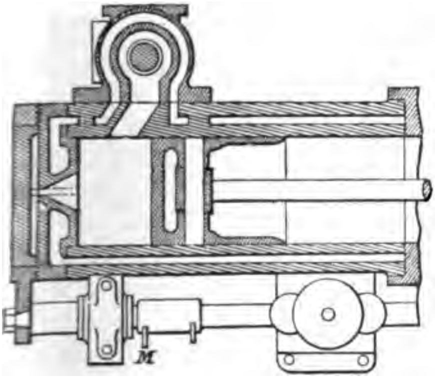
light volatile oils can be used, since the oil is injected to the cylinder without being vaporised or gasified by previous heating.

The cycle of operations performed in the cylinder is the same as in the Otto. The mechanism is different in detail, although a clear understanding of the methods of carrying out the several operations in the Otto will help us in the study of this motor.

The longitudinal sections, Figs. 64 and 67, show the cylinder, piston, petroleum reservoir C, supply tube F, air valve D, mixing tube H, and water jacket. The crank shaft, by bevel gear, drives a side shaft, which in its turn makes the other parts around the cylinder perform their various functions of *supply*, *ignition*, and *exhaust*.

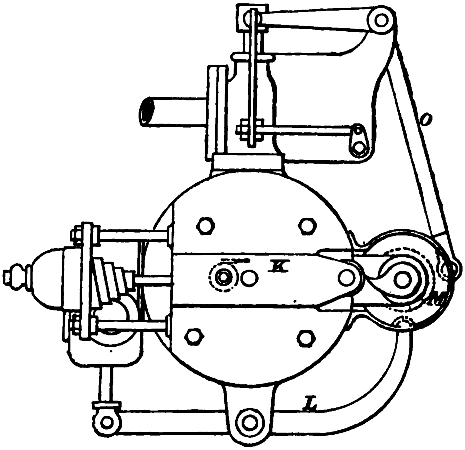
The *exhaust* valve is opened by the cam and lever L, Figs. 65 and 66.

FIG. 65.



SECTIONAL PLAN.

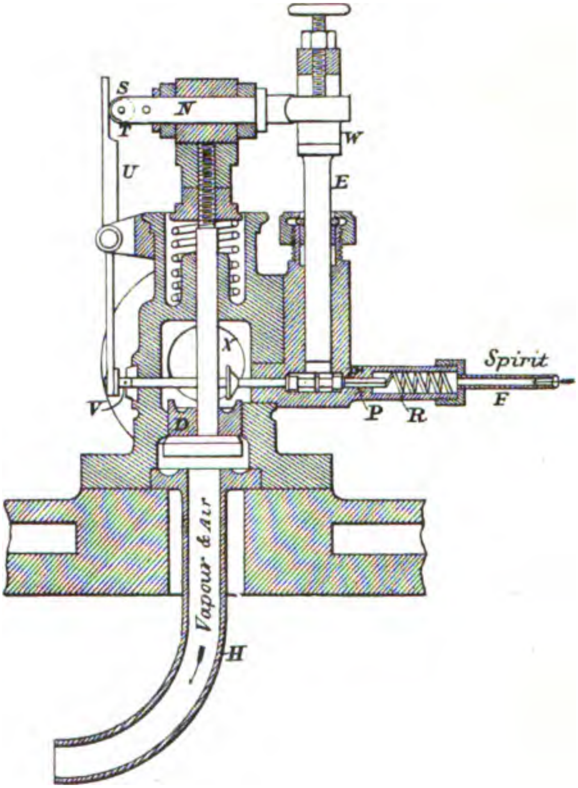
FIG. 66.



END VIEW.

*Ignition* is effected by the slide valve K, Fig. 66, which taking part of the rich charge during compression, into its passage, is forced about one inch towards the left by the hooked cam, Fig. 66. The portion of the mixture thus shut up is ignited by an external spirit lamp, and the slide valve, carrying this burning mixture, is shot back by a volute spring at its other end when released by the cam. Then the flame, entering the cylinder port, Fig. 65, explodes the compressed charges of petroleum and air in the cylinder at the right moment.

FIG. 67.



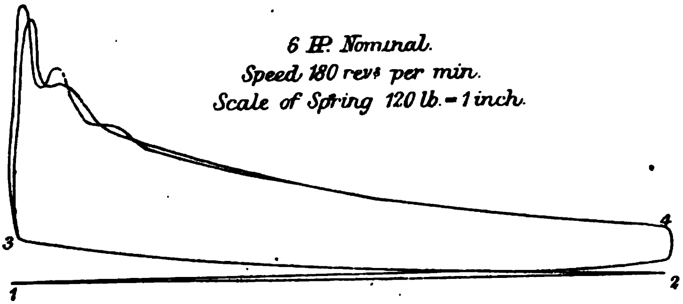
SUPPLY ARRANGEMENT.

The *supply* arrangement is seen by the enlarged view, Fig. 67. The valve P is held open by the spring R, which at the same time shuts the valve P′, so that the petroleum from the reservoir passes through F underneath the plunger E.

The cam M and lever O, Fig. 66, give the crosshead N, Fig. 67, a vertical motion. When the crosshead moves down, the roller S, on its end, knocks against the projection T, causing the lower end of the lever U to press the projection V inwards, and thereby close valve P and open valve P′. Next, the crosshead N, in its further descent, opens the air valve D, and at the same time the plunger E of the oil pump comes down, and forces the charge of petroleum below it through the open valve P′ against a cam X, which breaks it into spray. Then the piston in its suction or charging stroke draws the charge of air and spirit down the tube H, where it is mixed before entering the cylinder.

The indicator diagram, Fig. 68, taken from a Spiel engine giving 9 effective horse-power, will, with the above drawings, enable us to follow the action in the cylinder of this petroleum engine.

FIG. 68.



INDICATOR DIAGRAM FROM SPIEL'S ENGINE.

1st. *Charging* or *suction stroke.*—The piston travels forward from position 1 to position 2, Fig. 68, the cam M moves the cross-head N down, opening air valve D, whilst the plunger E forces the measured charge of spirit through valve P′, opened by lever U pressing on V. The mixture of spirit and air is drawn through tube H into the cylinder.

2nd. *Compression stroke.*—The piston during its return from position 2 to 3 compresses the charge to about three atmospheres, all passages to the cylinder being closed except the chamber in slide-valve K.

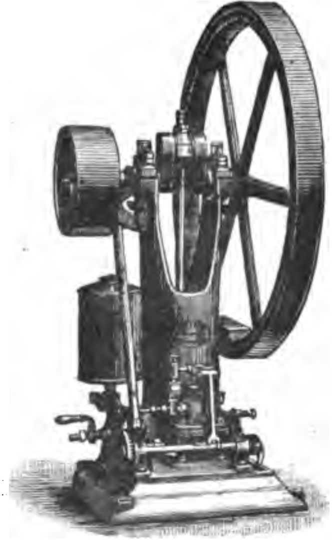
3rd. *Combustion* or *working stroke.*—The ignition valve K fires the charge at position 3 and the piston is driven forward to 4 when the exhaust valve is opened by the cam and lever L.

4th. *Exhaust stroke.*—The products of combustion are ejected from the cylinder by the piston in its return from position 4 to original position 1. The cam M is again ready for another charging stroke.

When the engine, running light, gets up too high speed, the governor forces the thick part of a slide between the lower end of lever U and the projection V, Fig. 67, so that V is not pressed inwards. Hence the valve P′ remains shut and P is open, when the plunger E comes down and forces the petroleum through the open valve P back towards F and the reservoir. Thus only air gets to the cylinder, and the supply of petroleum is entirely cut off until the speed falls to the normal. In other words, the consumption of petroleum is automatically controlled according to the power required, whilst the speed is kept uniform.

This engine works satisfactorily, the average consumption of petroleum spirit when the diagram, Fig. 68, was taken being at the rate of about one pint per brake horse-power per hour. When supplied with oil and started, it requires no further attention until the oil in the reservoir is consumed.

FIG. 69.



SPIEL'S VERTICAL ENGINE.

A vertical engine of this type, Fig. 69, is intended for purposes requiring less than 1 horse-power effective. It occupies small ground space—only 18 inches square—and is very convenient for many purposes in places where coal gas cannot be obtained and the work to be done is not sufficient to justify the buying of plant to produce cheap fuel gas for a gas engine.

## PETROLEUM AS FUEL AND WORKING AGENT.

In the foregoing pages we have considered the case of petroleum or hydrocarbons burned with air in the cylinder of internal combustion engines of the Otto type.

The uses of liquid hydrocarbons like petroleum are by no means limited to this solitary application. We should rather look upon *petroleum, or the gases from it, as the fuel of the future.* It may, when gasified, be used instead of coal as *fuel*, or of steam as *evaporating agent;* in fact, as *a substitute for both coal and steam* in the modern steam engine.

A successful practical application of this latter means of obtaining power is afforded by the

### Spirit Launch, "Zephyr" Type.

Messrs. Yarrow and Co., of Poplar, having their attention directed to the subject by the success of some small boats, in the United States, propelled by spirit vapour, undertook some *experiments to test the relative value of* HYDROCARBON VAPOUR *and ordinary steam as an* EVAPORATING AGENT *to produce work from heat in small motors.*

A small ordinary steam engine was used, with a friction brake on the fly-wheel to measure the useful power, whilst indicator diagrams taken from the cylinder showed the power developed by the working agent.

A vertical steam boiler was heated by a large gas-burner (Fletcher), so that the exact quantity of heat could be obtained and regulated by the gas-meter record.

In the one case steam was taken from the boiler to the working cylinder in the usual way, and the exhaust steam from the cylinder was condensed in a coil of pipe immersed in water, allowed to flow into a hot-well, passed on to the feed pump on the engine, and was forced back into the boiler, thus making a complete circuit. With constant water level in the boiler, the steam pressure was 50 lb. per square inch at start, and it was brought up to this at the end of each trial of three hours' duration.

In the case of petroleum, a copper coil was fitted inside the steam space at the upper part of the same boiler, so that the boiler efficiency should be the same as in the previous experiment. Petroleum spirit, of specific gravity ·680, was pumped into the copper coil, and vaporised by the heat of the steam. The vapour passed to the engine, worked the same piston in the cylinder, was led into a condensing coil, and passed to a hot-well, and finally pumped back into the coil inside the boiler.

The tests, made alternately with steam and spirit, gave the following results :—

| | Working Agent. | |
|---|---|---|
| | Steam. | Spirit. |
| Gas consumption in cubic feet per hour .. .. .. .. .. | 82·20 | 83·48 |
| Mean pressure of spirit in coil (lb. per square inch) .. .. | .. | 55·80 |
| ,, ,, steam in boiler .. .. .. .. .. .. .. .. | 37·99 | 30·07 |
| Mean speed in revolutions per minute .. .. .. .. .. .. | 312·6 | 552·2 |
| Tension on brake in lb. .. .. .. .. .. .. .. .. .. .. .. | 1·154 | 1·222 |
| Work obtained on brake in foot-pounds per minute .. .. | 2524 | 4722 |
| Indicated work in cylinder ,, ,, .. .. | 5·199 | 11·975 |

Thus, with nearly the same rate of gas consumption, the power obtained on the brake was in the ratio 5 : 9, for steam and spirit; that is, the same quantity of heat was turned into nearly twice as much work by the expansion of spirit vapour as by the expansion of steam under these conditions.

Petroleum spirit, being a complex mixture of various hydrocarbons, evaporates far more readily than water.

Proper care must be taken in using this spirit, as the more volatile vapours pass off at the ordinary atmospheric temperature.

Other vapours escape as the temperature rises, and there is not uniformity in the rate of evaporation when spirit is heated. Experiment shows that a given quantity of heat will evaporate nine times as much of this spirit as of water at atmospheric pressure. On the other hand, this spirit only expands to one-fifth the volume of vapour that water yields. Hence *a given quantity of heat can produce* $\frac{9}{5}$ *times the volume of vapour from petroleum spirit of specific gravity* ·680 *that it would of steam at the ordinary atmospheric pressure.*

Under similar conditions it is found that steam would have 25 lb. pressure and temperature 265° F., whilst petroleum vapour would be at 50 lb. pressure and temperature 220° F.

Moreover, spirit vapour has the advantage that it may be cooled as vapour to 130° F., under atmospheric pressure without condensing, and that it will not freeze at exceedingly low temperatures. Now we know that the greater the range of temperature through which we can cool a gas by its own expansion, doing work in a *perfect heat engine*, the greater the fraction of its sensible heat will be turned into work. To turn all its sensible heat into work would require infinite expansion to the absolute zero of temperature, which is impossible ; besides, the gas would be changed into the liquid and solid states long before that extreme degree of cold could be reached. With exhaust at atmospheric pressure, the lower limit of the working range of temperature in every case is the boiling point of the liquid. In the case of the spirit vapour used in the above experiments, this lower temperature was 130° F., so that work could be done by expansion from 220° F. to 130° F., that is, through a range of 90° F. Under these conditions steam could only be cooled to 212° F., through a range of 265°–212°, or 53° F. Therefore, since the efficiency *in a perfect heat engine* depends only on the working range of temperature, we see that this efficiency with steam and spirit would be in the ratio of about 5 : 9.

Again, owing to the small latent heat of evaporation of spirit, which is only one-ninth that of water, the loss of heat to the cooling water will be very much less when condensing spirit than with steam; but then less heat is given to the liquid spirit to convert it into vapour to begin with; so that, in the case of spirit vapour, smaller quantities of heat are being dealt with, and larger proportions converted into work by greater pressure during expansion.

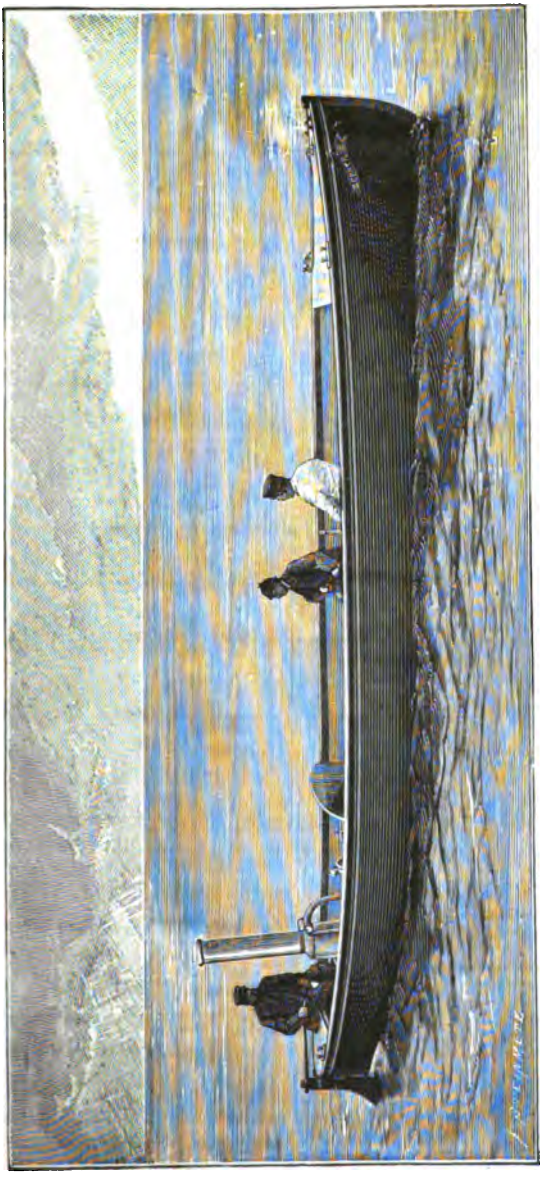
Hence, for a given power, machinery of much less weight is required with spirit than with steam. With due precautions to avoid explosions of inflammable vapour, petroleum spirit is found in practice to afford great convenience of working, owing to the rapidity with which it evaporates, as well as to its oily nature, enabling it to act as lubricant to the engine cylinder.

In the "ZEPHYR" TYPE of SPIRIT LAUNCH, Fig. 70, the engine, enclosed to avoid leakage, and placed near the stern, drives an ordinary screw shaft and propeller. The vapour *generator* is placed aft of the engine, and consists of a copper coil enclosed within a double sheet-iron casing, the space between being filled with asbestos or other non-conducting material. The petroleum supply is in an air-tight copper tank in the bow, and partly balances the engine at the stern.

The feed-pump of the engine supplies petroleum to the generator coil, where it is heated and converted into vapour, which drives the engine. The exhaust passes into two condensing pipes on each side of the keel, and is forced back, in the liquid form, into the supply tank in the bow, by the action of the engine. It is again pumped back into the generator, re-evaporated, expands and drives the piston, is then condensed and used over again.

The **mode of heating** may be varied to suit the fuel used, whether it be part of the spirit vapour, or the ordinary heavy hydrocarbon oils for burning. The simplest plan is to allow a small portion of the spirit vapour to pass by a valve into an ordinary ring gas burner, in which it is burned with a suitable proportion of air. The burner is placed under the vapour generator coil. In this form the action is automatic,

FIG. 70.



"ZEPHYR" SPIRIT LAUNCH.

and the engine will continue to work so long as there is any petroleum spirit in the supply tank.

But the storage of a large quantity of very volatile and highly-combustible petroleum spirit is not free from danger. This difficulty is overcome by using the *heavy mineral oils*, or ordinary paraffin oil, as *liquid fuel*. Air is forced by an air pump into the mineral oil tank, and the vapour is injected into the fire-box of the vapour generator. When the furnace is started, the liquid fuel is thoroughly vaporised before entering the burner. Then the gas is mixed with air and burns with non-luminous flame, the combustion being complete, as in a Bunsen burner.

The separate spirit that acts the part of working agent is vaporised in a small copper coil, the same spirit being used repeatedly, and the supply pump worked automatically by the engine. To avoid explosions, any slight waste due to leakage must be supplied by filling the tank only when the engine is stopped, and never while the engine is running, or when there is a fire under the generator.

In order to *start the launch*, a few strokes given to a little air pump connected with the supply tank, forces air charged with vapour into the burner, where it is ignited by a match. Then, work the spirit pump for a few seconds to put a little spirit into the generator coil, where it is immediately evaporated; the pressure rises and the engine begins to work, and does not require any further attention. Thus the engine can easily be started and the launch under weigh in about 2 to 5 minutes from the time of lighting up. The speed and pressure are regulated, and the engine stopped by simply opening or closing the injector valve for the supply of spirit vapour.

A "Zephyr" launch, 36 feet in length by 6 feet beam, built of steel, only weighs, with all machinery, one ton. About one-third of this total weight is due to tank and little engine, stowed away in the extreme bow and stern, thus allowing extra space for passengers under ordinary circumstances, or for men, arms, and ammunition in torpedo warfare.

Boats of this type run 8 miles an hour easily, and carry fuel for 200 miles or more if necessary. The consumption of fuel for burning is about 1·5 gallons an hour, that is one-third gallon per horse-power per hour. There may also be a little waste of spirit by leakage.

The combustion is perfect, and there is so little waste of heat by the burnt gases, that, when the engine is running at full power, one's naked hand may be held immediately over the funnel.

The lightness of the machinery, the rapidity of starting, the absence of smoke and steam, as well as the great saving in weight of fuel and storage space, all point to the importance of this type for launches, and especially for torpedo boats.

## LIQUID HYDROCARBONS AS FUEL.

Although light petroleum spirit is highly explosive, there is no such danger with the heavy hydrocarbons left after the removal by distillation from the crude petroleum of the burning oils and other useful products.

This petroleum refuse (crude astatki), called "liquid fuel," is an excellent fuel, surpassing coal in heating power, and is certain to take the place of coal, on board ship and for locomotives, wherever found cheap and plentiful, as in the region round about the Caspian Sea.

Crude liquid hydrocarbons of various names have also been successfully applied for heating and metallurgical operations with marked economy of fuel and great saving of time, giving *better iron*, free from scale and sulphur—very high temperatures being quickly obtained.

Such applications are, however, beyond the province of this book, which deals rather with the **methods of utilising oil or hydrocarbons to produce power.**

Besides the primitive and wasteful burning of oil in the liquid state, with incomplete combustion and deposit of soot, two other methods have been adopted:

(*a*) *Injection of oil as fine spray with steam and air;*

(*b*) *Conversion of the oil into gas by heat before use.*

(*a*) As early as 1863, Mr. W. B. Adams introduced the injection method by compressed air. In 1867 this was tried, with shale oil and superheated steam, in the launch *Oberon*, giving an evaporation of 13 lb. of water per lb. of oil.

About the same time, Isherwood, of the United States Navy, made experiments on the gunboat *Pallas*, showing the great economy of oil, over the best anthracite, as regards storage, convenience of handling, and heating power. (See page 353.) Here the method proposed by Colonel Footes was employed. A mixture of air, superheated steam, and hydrocarbon vapour was injected through small pipes perforated with numerous orifices, and exposed to the heat of combustion in the furnace.

In New York, fuel oil, from the oil refineries, of specific gravity 0·818 and flashing point 218° F., costs about 1·75*d.* per gallon. This oil is used to produce steam in stationary boilers. The oil is forced into the furnace in the form of fine spray by steam or compressed air, through injectors, and mixed with the air required for the combustion. In practice 1 lb. of this oil is worth about 1·3 lb. of good coal for heating purposes. (See page 353.)

The locomotives on the South-Eastern Railway in Russia, as well as steamers throughout the Caspian Sea region, burn crude petroleum refuse carried in tanks. A flexible pipe from the tank leads to an arrangement of oil and steam pipes in the fire-box. The oil is injected as fine spray into the fire-box by steam jets, the air for combustion being also drawn in. Mr. Urquhart points out the great convenience of the petroleum refuse here used, and his results show that its practical heating power is much higher than that of the same weight of anthracite. (See page 354.)

An example of this method (*a*) of burning oil fuel* is afforded by the "Bailey-Friedrich" **petroleum steam motor**, shown in Fig. 71 driving directly a "Manchester dynamo machine for electric lighting or power purposes.

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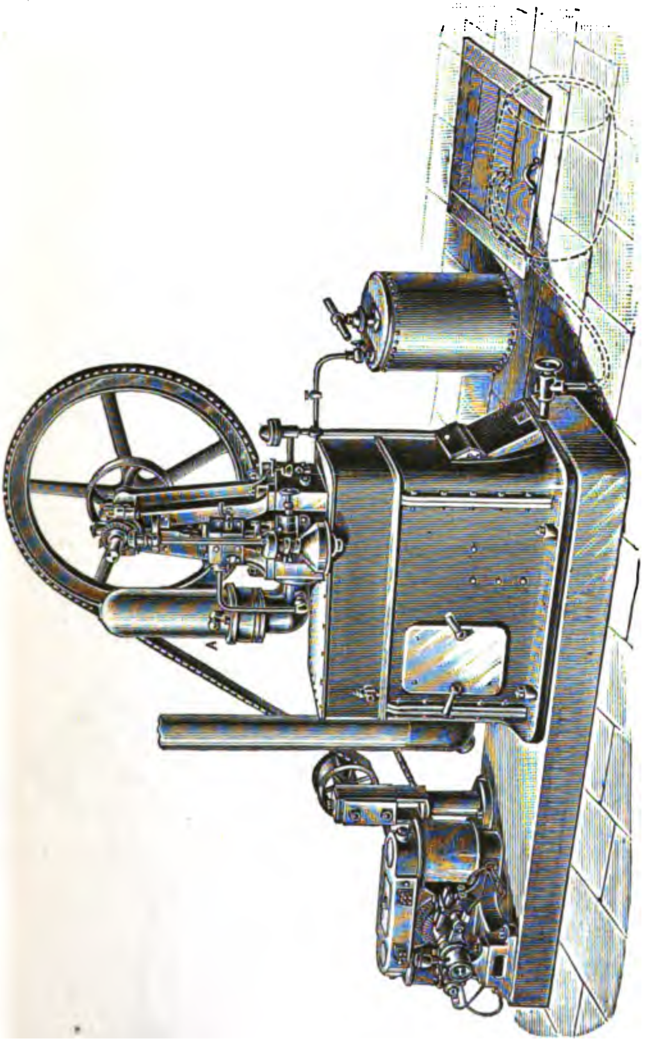
* The wide field of usefulness in the application of oil-fuel to the steam engine, both for locomotives and on board ship, necessitates this brief reference to the subject, for the sake of contrasting the mode of working with that of the gas motor.

FIG. 71.

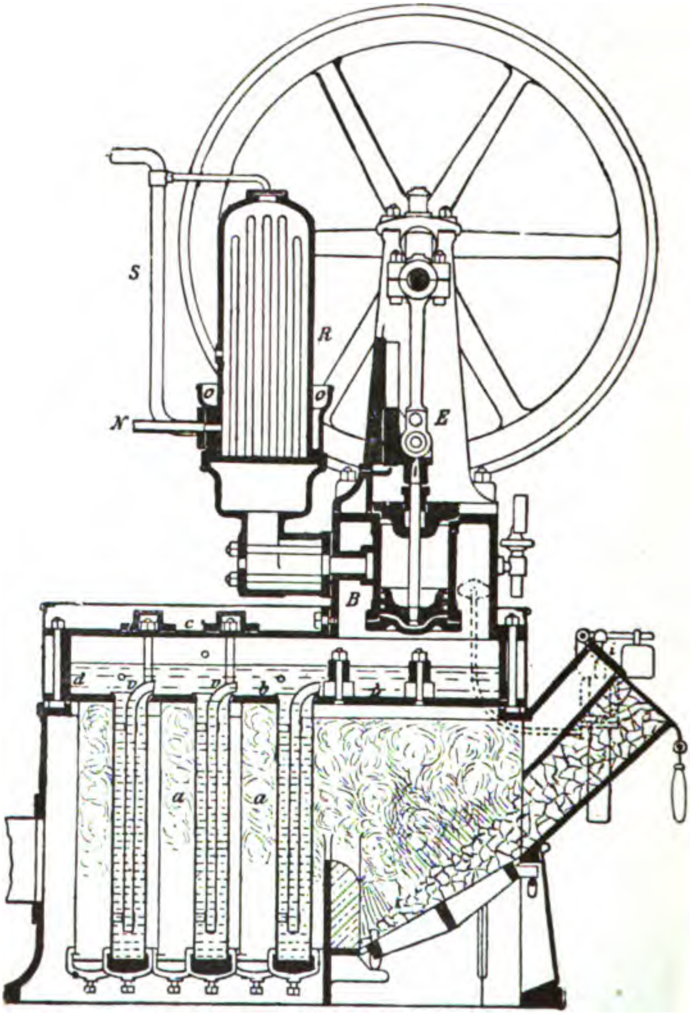


BAILEY-FRIEDRICH PETROLEUM MOTOR.

The common refined petroleum to be used is kept in a tank well *below* the level of the furnace flame in the boiler.

The oil is injected into the furnace in fine spray by a jet of steam. It is there ignited, and heats the boiler tubes. To get up steam when starting, the jet inside the fire-box is lighted,

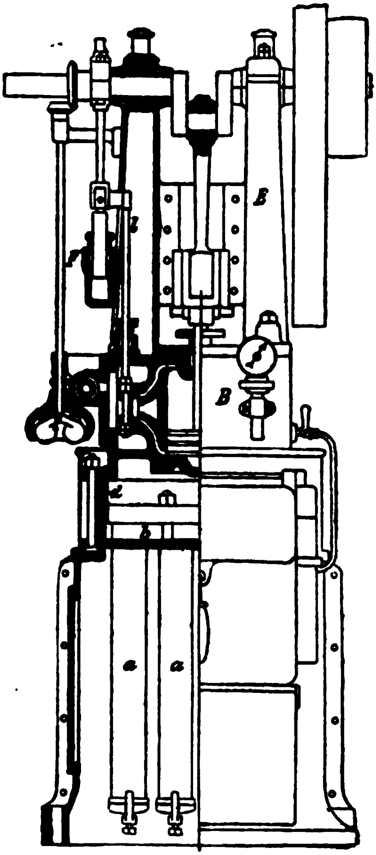
FIG. 72.



SECTIONAL ELEVATION.

some air is compressed and forced into the jet by a hand pump until sufficient pressure of steam is obtained; then the motor works automatically by a diaphragm valve which

Fig. 73.



End View.

regulates the supply of steam to the jet. The consumption of oil is about one quart per horse-power per hour.

This petroleum steam motor is simply a modification of the Friedrich steam engine, shown in section and end view

Figs. 72 and 73. In this engine coal is the fuel, and steam the working agent.

The *boiler* consists of a steel plate *b*, Figs. 72 and 73, into which are fitted perpendicular field tubes *a*, *a*. A steel frame *d* rests on *b* and carries the steel plate *c*, all being held together by bolts and screw nuts, so that the upper plate can be readily taken off and the boiler inspected and cleaned. The bent tubes *v*, *v*, Fig. 72, maintain a good circulation of water. On the top of the boiler the steam dome B is in the same casting with the *steam cylinder*, which is constantly surrounded with steam, thereby preventing condensation. The crank shaft, on the pedestal E above the cylinder, works the feed pump F.

The exhaust steam passes into the small tubes of the surface condenser R, surrounded by cold water, and when condensed the water is forced back into the boiler by the feed pump. The water line is kept up by adding about two quarts of water per horse-power per day.

The furnace has a hopper which holds fuel for a run of two hours. The fuel is partly coked before it drops on the grate, where it burns gradually.

Automatic regulation of the fire is effected by a small piston *i*, which is raised when the steam pressure exceeds the normal 70 lb., and opens a damper door to admit air above the fire and so lower the pressure. When the normal steam pressure is reached, the door closes again.

This compact arrangement with the Manchester dynamo is suitable for powers up to 12 useful H.P., and is said to work with a consumption of 5 lb. of coal per effective horse-power per hour—a comparatively low figure for a steam engine of such small power in ordinary practice.

(*b*) In the *spray injection* method of using oil-fuel, unless the liquid hydrocarbon is thoroughly vaporised before ignition, an excess of air is necessary to ensure perfect combustion of the finely-divided liquid spray. On this account the oil is sometimes vaporised by passing it through pipes in the furnace.

In order to use any kind of oil or fat as fuel, it is melted and passed into a separate generator or retort heated in a furnace, to convert the liquid hydrocarbons into gas. A rich OIL-GAS issues from the retort, and may be burned directly with air, or cooled and stored up for future use.

Oil-gas is enriched and improved if the liquid oil be injected by a jet of steam into the generator or heated retort. The gas produced, when washed, cooled, and mixed with air, is admirably suited to drive the ordinary internal combustion engine. (See pages 391 and 398.)

# CHAPTER V.

## HISTORY OF COMBUSTION AND CALORIC ENGINES.

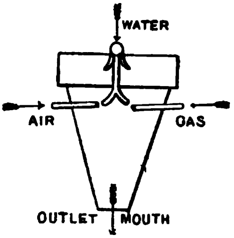
### Brief Sketch of Early Inventions.

IT may be said that the history of HEAT ENGINES begins with the discovery of cannon—the first combustion engine. This should rather be regarded as a *powder machine* which performs work by the expansion of the gases derived from the *explosion* of gunpowder. Here the working substance, gunpowder, possesses potential energy of chemical separation, which, on ignition by a spark and by subsequent combustion, is converted into kinetic or heat energy. In some of these machines the *energy of the explosion was used indirectly*, a partial vacuum being first formed by cooling the products of combustion after expansion, and the atmospheric pressure then utilised to drive down a piston doing work.

In 1678, a powder machine for raising water in this way was *proposed* by Abbé HAUTEFEUILLE, although there is no evidence to prove that he ever had a machine *constructed*. HUYGHENS was the *first* to use a *cylinder and piston* in his powder machine, about the year 1680; and PAPIN described, in the 'Proceedings' of the Leipsic Academy, in 1688, a similar arrangement provided with regular valves. It was found that one-fifth part of the air always remained in the cylinder, and opposed the free descent of the piston under atmospheric pressure. Such apparatus was exceedingly rude, and the risks of accidental explosion with gunpowder so great, that Papin does not appear to have achieved any economical or useful results.

About the *earliest attempt to obtain motive power from inflammable gas derived from the distillation of coal*, in fact one of the first practical uses or applications of coal-gas,* was that of an Englishman, JOHN BARBER, who, in 1791, invented "*an engine for using* INFLAMMABLE AIR *for the purpose of procuring motion.*" He heats *coal*, *wood*, *oil*, or any other combustible substance in a metallic *retort*, and conveys the vapour or product to a *receiver*, where it is collected and *cooled* by a surrounding cistern of water. By means of an air pump and *compresser*, this inflammable gas and atmospheric or common air, in *proper proportions*, are forced through separate pipes into another vessel called the *exploder*, Fig. 74. The mixture is here ignited, and "rushes out with amazing force and velocity" against the vanes of a paddle-wheel, which is thus made to rotate rapidly, working the pumps, and communicating motion to any machinery. "The fluid stream is considerably augmented, both in quantity and velocity, by water injected" or pumped into the exploder through a small pipe. This water is also intended to *cool* the pipes and mouth of the *exploder*. He also mentions in his patent that the fluid stream issuing from the mouth of the exploder may be injected into furnaces for smelting ores, or passed out at the stern of a ship, and thus propel the ship by the reaction against the water.

FIG. 74.



BARBER'S EXPLODER.

In 1794, ROBERT STREET took out a patent, No. 1983, for the FIRST *practical internal combustion engine with a motor cylinder and piston.* A small quantity of petroleum oil or spirits of turpentine is admitted to the cylinder and evaporated by heat applied to the bottom of the cylinder, air being drawn in during the upward motion of the motor piston connected by a lever to a pump. Outside this cylinder there is a *flame*, which is brought into contact with the mixture of air and inflammable vapour at the proper time by a *slide-valve*, and so ignites the explosive mixture. The piston is thrown up by the force of the explosion, and drives down the pump piston to raise water. The arrangement is crude and imperfect, and although the idea is good, nothing satisfactory was obtained in practice.

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* In 1726, Stephen Hales pointed out that by the distillation of coal an inflammable gas is evolved. The first to practically manufacture coal gas for lighting purposes was William Murdoch, a Scotchman, living at Redruth in Cornwall. Afterwards he improved his process of manufacture, and in 1798 the Soho factory, near Birmingham, was for the first time lighted with coal gas. The streets of London were first lighted with coal gas in 1812, and Paris in 1815.

In 1799, PHILIP LEBON, an ingenious French artisan, devised and patented a gas engine which was practically identical, in principle and construction, with one of the most successful of pioneer gas engines—the Lenoir. He had already patented a gas retort or furnace for the production of illuminating gas. Lebon distils the carburetted hydrogen and other gases from coal, and stores them in a reservoir. *By means of two pumps he compresses a measured charge of this gas with a charge of atmospheric air, separately into a recipient;* here the constituents get mixed, and the mixture is introduced into the cylinder alternately on each side of the piston, and fired by the electric spark. The combustion products expand, driving the piston backwards and forwards, doing work on both sides, as in a double-acting steam engine cylinder. Both the pumps and the electric machine are driven by the engine.

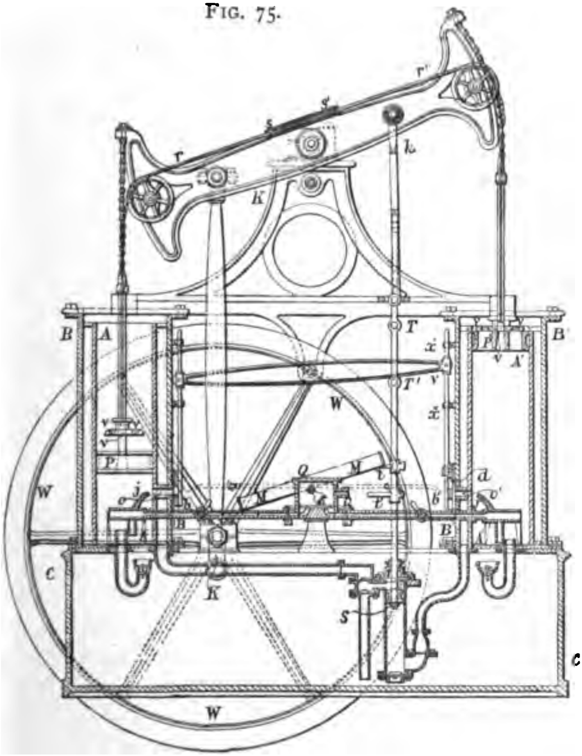
This gas engine will compare very favourably with our modern ones. It was entirely self-regulating, and—mechanically as well as theoretically—a success. It was found to work well, but at that time coal gas had not been introduced as an industrial product for lighting purposes, and the expense of preparing it specially for the engine rendered the scheme a practical failure; besides, the only source of the electric spark known at that time was static electricity, which was so very uncertain and dependent on atmospheric conditions.

Lenoir's engine, patented in 1860, was practically a reproduction of Lebon's.

## *Brown's Vacuum Engine.*

In 1823, SAMUEL BROWN invented a most important gas engine. It is an *atmospheric engine*, with water-jacket to cool the cylinder. A gas jet is kept constantly burning outside the cylinder, and ignites a mixture of inflammable gas and air below the piston. Part of the expanded gases is allowed to escape through valves in the piston; then, by cooling with water, a vacuum is effected, and the *atmospheric pressure* outside *drives down the piston.* In his patent, No. 4874 of 1823, he describes three applications of this principle to different kinds of machinery: first, to turn a water wheel; second, to raise water; and the third, to drive pistons. Fig. 75 shows

FIG. 75.



a sectional elevation of the arrangement for this last purpose.

This engine is double acting, a piston being attached to each end of the crossbeam or lever by a rod and chain. The arrangement somewhat resembles Newcomen's atmospheric engine. B, B′, are the outer cylinders, open at their tops; A, A′, the working cylinders, each with piston P, having the valve V, opened at the top by rod *r* from the spiral spring *s*, *s*′; *v*, *v*, very small valves in the upper side of V; *j*, gas jet communicating with the gas supply box Q, by the pipe *a*; *b*, gas burner constantly lighted to ignite gas at *j*, through the orifice *o*, when uncovered by the slide *d*, actuated by tappet T, on piston-rod *k* of the double-acting pump S, which forces water from cistern C into the water-jackets and over the cylinders. Some water falls through the valves V′, V′, to bottom of the cylinders, whence it returns to the cistern through the syphons shown in diagram; but experience showed these were unnecessary. K is connecting-rod from beam to crank-shaft K with fly-wheel W; *t*, *t*′ are arms which move tube M, containing mercury, and turning the forked arm or tumbler F, which moves the slide over the orifice *a* or *a*′, thus regulating the supply of gas to the working cylinders from the box Q. With the piston P in its lowest position (as in the left-hand cylinder, Fig. 75), the valve V is held open by the action of the spring *s*, *s*′; the slide is off the orifice *a*, allowing the gas to flow through the pipe into the burner *j*, where it is ignited through the opening *o*, by the flame *b*, outside the cylinder; whilst in the other cylinder A′, the piston P′ is at the top, the valve V′ and the orifices *a*′, *o*′, are closed.

As the piston P is moved upwards, the tappet T comes down against the little beam, draws the slide *d* over the orifice *o*, and opens *o*′. A strong flame continues to burn the gas at *j*, whilst the mercury flows along the tube M, turned by the tappet *t*, and the tumbler F moves the slide over the orifice *a*. Part of the rarefied air in the cylinder A escapes through the piston valves. When the piston has reached its highest position, the valve V is closed, and by this time the pump S has forced water through the passages and over the top of the cylinder. This suddenly causes a partial vacuum beneath the piston, and as the external atmospheric pressure drives it down, the orifice *o* and the valve V are re-opened. Now the piston P′ is at the highest part of its stroke; and a similar series of operations goes on in both cylinders, the pistons working alternately.

Subsequently, in 1826, Brown improved his machinery, and used auxiliary cylinders, in which the air and gas were mixed before being drawn into the motor cylinder and exploded. Brown had worked long and hard, but only achieved temporary success and pecuniary reward. His engine attracted much attention and admiration, and was used to raise water and to propel boats on canals, as at Croydon, Eagle Lodge, and other places.* In some experiments on the Thames, from Blackfriars Bridge, a speed of seven or eight miles an hour was attained.

A company was formed and hydrogen gas used; but the expense of procuring gas was found to entirely prevent its application to prime motors instead of steam, and hence the company was dissolved, although Brown was still sanguine as to ultimate economy.

In 1833, WRIGHT patented a double-acting gas engine, in which the combustion products of a mixture of gas and air act directly on each side of the piston, like the steam in a steam engine cylinder. The drawing in his patent, No. 6525, shows very complete details of the working parts, and usual devices of connecting-rod and crank for transmitting motion from the piston to the rotating shaft and fly-wheel. This machine has a water-jacket, and water passes down the interior of the piston-rod and piston, to keep them cool. Pumps compress the gas into one reservoir, and the air into another.

A centrifugal governor controls the admission of the gas and air, under pressure, into the combustion-chambers, so that the total quantity may remain the same, and be mixed in proportion for properly doing the work. These combustion-chambers are spherical cylinders, one fixed near each end of the working cylinder, and the mixture is lighted at a touch-hole by a small flame kept constantly burning. The intention was to have an explosion every stroke, and the piston actuated by the expansive force of the gases. But this force would be greatly diminished by the condensation of the gases in contact with the cold sides of the cylinder, piston, and rod.

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* See full account in the *Mechanics' Magazine*, vols. ii. 1824, vii. 1827, xvii., and xviii.

It does not appear that this engine was ever made to work.

WILLIAM BARNETT'S patent, No. 7615 of 1838, marks a decided advance in the history of gas engines, being much more complete and better illustrated than any preceding one. Three forms of gas motor are described, the first is single acting, and the other two double acting.

An important feature of Barnett's engines consists in *compression* of both air and gas by separate pumps into a receiver; also, in the third form, the motor piston completes the compression of the explosive mixture in the motor cylinder itself before ignition, which takes place at the commencement of each stroke, as the crank passes the dead centre.

Barnett's igniting cock is also worthy of note. The mixture is fired by means of a hollow conical plug, within which a flame is maintained. As this plug turns to the cylinder the compressed charge is ignited, and the explosion puts out the flame, which is relighted by a constant external flame as the plug turns further round. (See page 218.)

About this time we find a whole series of patents for hydrogen motors, the cost of hydrogen and oxygen gas making them all mere curiosities. For example, in patent No. 6875 of 1835, COOPER describes an engine in which one part of oxygen and two parts of hydrogen are ignited to produce a vacuum alternately on each side of a piston. As in all these early patents, the language about mechanical details is vague.

Again in 1841, JOHNSTON describes a machine which might be called a *condensing gas engine*. To obtain power he would introduce an explosive mixture of hydrogen and oxygen under a piston in a motor cylinder, and then fire the charge, driving the piston up to the top of cylinder. Immediately after the explosion a vacuum is produced by condensation of the water formed, whilst another explosive mixture is introduced and fired above the piston, driving it down, utilising the effect of the vacuum. The engine would thus be double-acting, the explosive mixture being drawn in, ignited, and the water produced condensed, alternately above and below the piston.

Other devices were proposed by Robinson, in 1843; Reynolds, 1844; Perry, 1845; Brown, 1846. These few examples serve to mark the ideas on the subject at the time.

## Caloric Engines.

A different type of prime motor, in which air is the working fluid, was now prominently before the public as a rival to the steam engine.

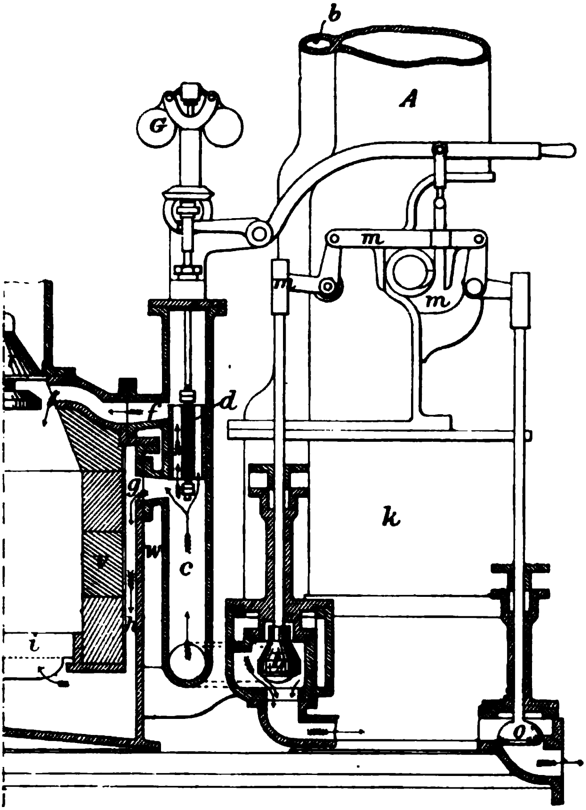
The first important HOT-AIR ENGINE was that devised by Sir GEORGE CAYLEY, and described by him in 1807. He gives full details and description of the improved form of this engine in his patent taken out in 1837. Compressed air is forced by a pump into a strong air-tight furnace, where it is heated and supports the combustion of the coals through which it passes. The hot compressed air and products of combustion, at from 500° to 800° Centigrade, are thence admitted directly into the working cylinder, where they drive the piston, doing useful work, and are rejected by the exhaust at 250° or 300° Centigrade.

The power obtained is the difference between the power calculated from the diagram of the working cylinder, and that indicated in the pump cylinder as spent in compressing the cold air and forcing it into the furnace.

Cayley's engine is essentially the same as the modern "BUCKETT" CALORIC ENGINE, of which Figs. 76 and 77 show sectional elevations.

The fire F, contained within the closed retort, receives air to support combustion, by means of the air-pump A, the piston of which, on its up stroke, compresses and forces air through the passage *b*, Fig. 76, whence it is delivered to the retort by the passage *c*. In this passage a cylindrical distributing valve *d* is capable of being moved upward or downward by the direct action of the governor G. The function of this valve is to determine how much of the stream of compressed air is to be

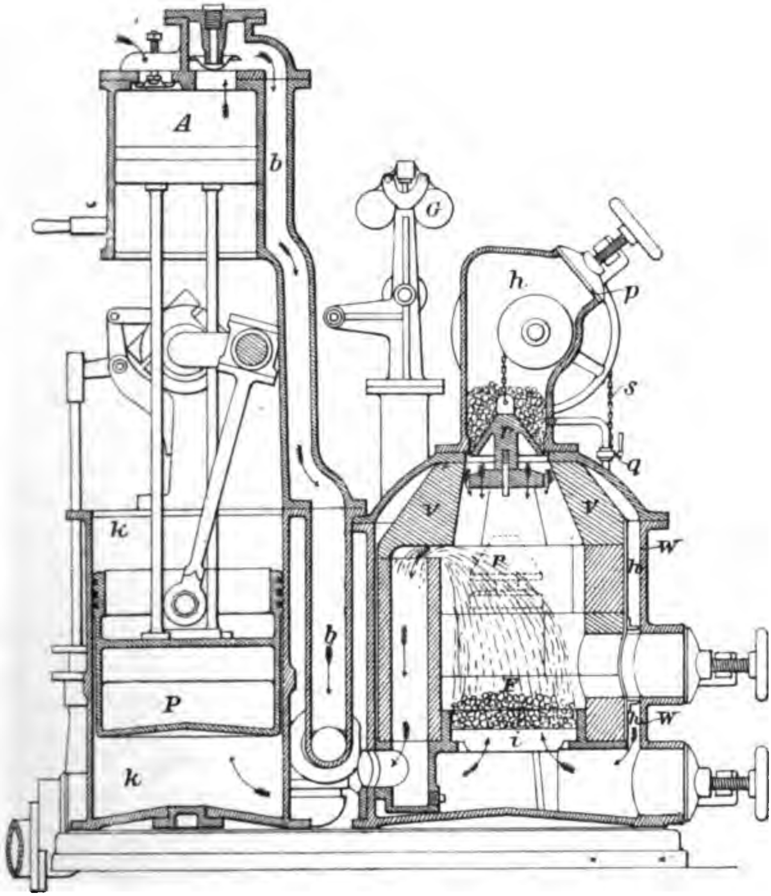
FIG. 76.



SECTIONAL ELEVATION OF GOVERNOR PIPE, INLET VALVE AND PART OF GENERATOR.

delivered through the ports *f* and *g*. The air passing through *g* descends the annular space *h* between the fire-brick lining V and the casing of the retort W, whence it ascends through the

FIG. 77.



SECTIONAL ELEVATION OF CYLINDER AND GENERATOR.

grate bars *i*, and helps to burn the fuel. The products of combustion pass to the upper part of the retort, where they are met by the incoming air from port *f*, which ignites the unburnt gases, and completes the process of combustion. The fire may be checked and regulated by sending a larger proportion of air by *f* above the fire than by *g* and *i* through it.

The burnt products and heated air admitted by the inlet-valve L, pass into the cylinder *k*, under the piston P, and drive it up by their force of expansion, in the same way as the piston of an ordinary steam engine.

The exhaust valve O allows the gases to escape from the cylinder as the piston descends and drives them out. The inlet valve L is automatically operated by the cam and levers *m*. The cold compressed air, on its way to the fire F, through the passage *b*, passes into an annular space around the casing of the valve L, the object being to cool the casing, and at the same time save the heat which would otherwise be radiated and lost.

The retort is fed with coals by means of the hopper *h* and the door *p*, Fig. 76. When the hopper is filled with a charge of fuel, the door *p* is closed, and a small cock *q* is opened. This allows some of the hot air to enter the hopper, and, by equalising the pressure, puts the conical valve *r* into equilibrium, so that, upon lifting the chain *s*, the valve can descend and let the fuel fall upon the fire.

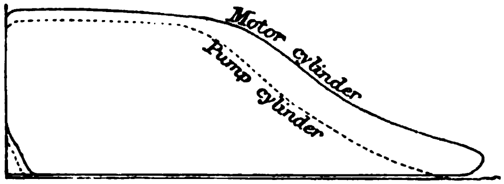
Compressed air at such high temperatures as 800° or 900° C. soon damages the air-tight packing, as well as the valves and pipes through which it passes. Ordinary metallic slides are out of the question, as it would be impossible to lubricate them. The valves used in this engine are circular masses of iron, capable of being raised or lowered on to seatings of conical form. These cause noise, particularly when the engine is running quickly, and this is a serious objection to the engine for many commercial purposes. Mr. Charles Ingrey, the engineer of the Caloric Engine Company, has hit upon the idea of using a block of plumbago as a slide valve, and states that, after several months of continuous use, there was no appreciable reduction of the valve by friction. The continuous dropping of the valve on its seating tends to make an air-tight joint. The plumbago acts as its own lubricant, and it is not likely to be affected by the temperature of the hot air.

In a special trial of a 12 nominal H.P. vertical double-cylinder caloric engine, the gross indicated power from diagram of working cylinder was 20·19 H.P., and that of the pumps 11·38 H.P., leaving 8·81 H.P. as the net indicated result from the two cylinders, whilst the effective brake horse-power was 5·9 H.P., giving a mechanical efficiency of 67 per cent. The consumption of coke was 2·5 lb. per hour per indicated horse-power, and 3·7 lb. per hour per brake horse-power.

The mean indicated pressure on pistons was 15·37 lb. per square inch, and that in pumps 15·9 lb. per square inch; the cross sectional area of the working cylinders being twice that of the pumps.

The hot air supplied to the working cylinder was about 630° C., and at the end of the stroke rejected at 480° C., giving a range of 150° C., so that a perfect heat engine working between these temperatures could only convert 16 per cent. of the total available heat into mechanical energy. The range of temperature through which the heat thus falls determines the highest possible efficiency to be expected of any heat engine.

FIG. 78.



SPEED 61 REVOLUTIONS PER MINUTE)
INDICATOR DIAGRAM FROM "BUCKETT" CALORIC ENGINE.

As will be seen by the indicator diagrams from this engine (Fig. 78), the hot air is admitted during the first half of the stroke, and then, after cut-off, allowed to expand to twice its original volume before being rejected. These diagrams are samples of a series taken from an engine during a run of about five hours under a brake of 14 H.P. The initial pressure in the working cylinder is 28 lb., and the mean pressure 18 lb. per square inch. The power obtained is the difference between the power calculated from this diagram and the power indicated in the pump cylinder, which is spent in compressing the cold air and forcing it into the furnace. After this deduction the consumption of fuel is given as 1·8 lb. of gas-coke per hour per indicated horse-power, and 2·54 lb. hourly per brake or effective horse-power. Therefore, of the total quantity of heat generated by burning the fuel, less than 8 per cent. is turned into useful effective work.

The available mean pressures in the motor cylinder are low, and, unfortunately, as the pressure is increased, a much larger proportion of the power is spent in compressing the air. With the initial pressure 28 lb. per square inch, more than 50 per cent. of the indicated power is thus required, and it would take even more than 65 per cent. to compress the air up to 100 lb. per square inch, whilst the other sources of waste would be correspondingly high.

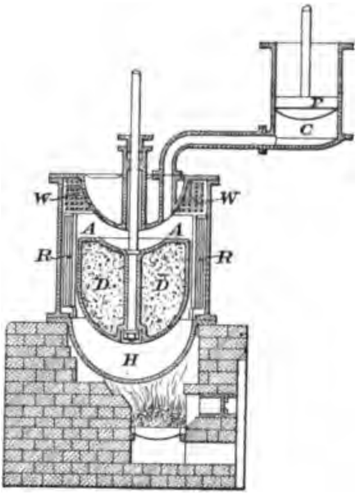
These engines get out of order owing to over-heating; and great waste of heat occurs. The sizes range from ½ to 12 horse-power. Several engines of this type are used on lightvessels and in lighthouses, to operate the Siren fog signals; but they cannot be expected to supersede the steam engine.

### *Stirling Engine.*

In 1827, Dr. ROBERT STIRLING, a Scotch minister, assisted by his brother, Mr. JAMES STIRLING, an engineer, patented, and in 1840 improved, a hot air engine, in which we find the ingenious expedient of the *regenerator* first used. The first patent, No. 5456 of 1827, describes the detailed construction of air vessels opening to the cylinder on opposite sides of the motor piston, also the mode of working or procuring motion of the crank shaft and fly-wheel by alternately heating and cooling air. The piston-rods of the working cylinder and air vessels are connected with a crank on the main shaft by parallel-motion, working beam and connecting rod. The crank shaft carries a fly-wheel and a secondary crank, so adjusted and placed in advance of the main crank that the stroke of the plunger is half completed when the piston is commencing its return stroke.

The diagram[*] (Fig. 79) shows, in a simple form, the main features of this early Stirling engine. It consists of two cylinders of different diameters. The small one, C, is the working cylinder. The large cylinder is divided into two compartments by a hollow plunger or displacer D, which is filled with brick-dust or other low conductor of heat. The air is heated in the space H, between the plunger and the bottom of the cylinder, which is exposed to the direct action of the fire. The plunger is made to fit closely into the upper end of the cylinder A, which acts as the air-vessel. This compartment or air-vessel A always communicates freely with the working cylinder C, and is kept cool by the refrigerator W, which consists of a spiral coil of thin copper tubing, through which cold water circulates. The communication between the two compartments of the large cylinder is through R, the **regenerator.**

FIG. 79.



The idea of the regenerator—that is, of storing and restoring heat by some means without losing it—is the great invention of Stirling, and in its application to the various branches of industry is one of the greatest triumphs of engineering. In its simplest form it consists of thin plates of metal, glass, or layers of wire gauze, exposing a large surface to obstruct the passage of heat. To these thin plates the hot air gives up most of its heat when passing out, and regains it from them on entering, so that the ***regenerator stores and restores the heat,*** and a great change of temperature can thus be produced without much loss of heat energy.

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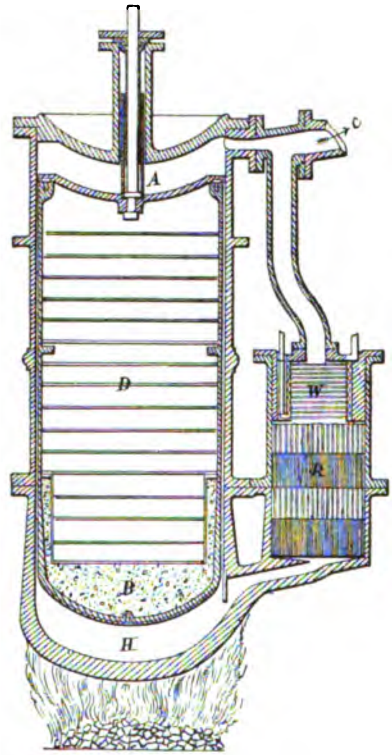
[*] See Rankine's *Manual of the Steam Engine.*

In the second patent, No. 8652 of the year 1840, the regenerator R, Fig. 80, and refrigerator W, are shown separate from the displacer plunger D.

The regenerator is constructed with broad plates of sheet iron about $\frac{1}{40}$ inch in thickness and $\frac{1}{50}$ inch apart. The refrigerator W consists of copper pipe $\frac{1}{8}$ inch diameter inside and $\frac{1}{4}$ inch outside, about $\frac{1}{20}$ inch apart, and through which cold water circulates. The displacer plunger D is made of iron, lined on the lower end B with brick dust; and the piston-rod has a leather collar at the top of the air-vessel, with an oil-vessel below, to prevent escape of air.

FIG. 80.



STIRLING DISPLACER AND REGENERATOR.

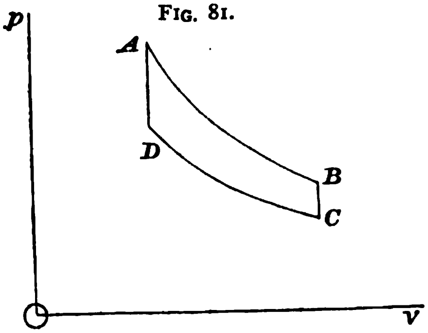
Compressed air is pumped into the air-vessel, at a pressure of 150 lb. per square inch, to supply waste by leakage.

The piston-rods of the displacer and driving piston are attached to cranks set at right angles to each other on thema in shaft which carries a fly-wheel, not shown in Figs. 79 and 80.

As the displacer D moves towards the top of the large cylinder, it forces some of the air from A through the regenerator, where it is partly heated, into the lower compartment, H, of the large cylinder, which is kept by the fire at the constant maximum temperature T. The air expands, and the *pressure thus produced by* HEAT *is transmitted through the whole mass of air to the working cylinder* C, *and raises the small piston* P, *thus doing useful* WORK. Now, as the plunger D descends, it forces the hot air out of H, through the regenerator, R, to the air-vessel and working cylinder. The air leaves the greater part of its *heat stored up* in the regenerator, and is further cooled by the water in the refrigerator and air-vessel to the lowest temperature T′, so that its pressure falls. The air is next compressed to its original volume by the piston P in its descent, whilst the refrigerator takes away the heat and keeps the air at the lowest temperature T′. Again, the displacer D in its upward stroke forces the air from A down through the regenerator, which *restores heat to the air* before reaching H, where it is again further heated by the fire.

In this way the working air passes up and down through the regenerator, and being alternately heated and cooled is the means of transforming heat into mechanical work.

FIG. 81.



The cycle in the Stirling engine is easily followed by the ideal indicator diagram, A B C D, Fig. 81, which shows the relation between pressure and volume of air in the working cylinder during a complete series of operations.

1st Operation : A B—*Expansion of air at higher constant temperature.*

Starting with the displacer plunger D at the top of its stroke, the air expands, driving up the piston P in cylinder C, and doing useful work, whilst the air is maintained at a high constant temperature, about 340° C., by heat continuously supplied to it in H by the fire. The energy thus stored up in the fly-wheel carries the engine through the rest of the cycle.

2nd Operation : B C—*Cooling the air, at constant volume, to the lower temperature* T′.

During the downstroke of the displacer D, the hot air is forced from H, *up through the regenerator* R, to the refrigerator and air vessel A at the cold end of cylinder. The layers of wire gauze absorb the heat and store it up directly as heat, thus greatly reducing the temperature of the air before it enters the refrigerator to be further cooled to the lower temperature T′, when the displacer D reaches the bottom of its cylinder, and the non-conducting material B keeps away the heat of the furnace.

3rd Operation: C D—*Compression of air at lower constant temperature* T′.

While the displacer D is at the bottom of its cylinder, the working piston P moves down and compresses the air kept cold by the refrigerator, which carries away the heat. Here work is done on the air at the expense of energy stored up in fly-wheel and some heat is rejected to the refrigerator at the lower temperature.

4th Operation : D A—*Heating the air, at constant volume, to the higher temperature* T.

During the upstroke of the displacer plunger D, the air from the cold end of cylinder is forced down through the refrigerator, which gives up the heat previously left in it. The temperature of the air is thus raised to that of the hot chamber H, which the air enters, to be further heated and do work by its expansion, again driving up the working piston P at the higher constant temperature T, the pressure falling along the curve A B.

The excess of the work done in expansion over that spent in compression is available to drive the engine and do useful work. This is represented by the area of the diagram A B C D, which clearly increases with the range of temperature, other things being equal. It can be proved (Chap. XVI.) that in the Stirling engine the fraction

$$\frac{T - T'}{T}$$

of the total quantity of heat supplied is converted into work done on the piston, where T and T′ are the absolute temperatures at which the working air receives and rejects heat.

This cycle of operations, like Carnot's, is reversible, that is, the air may be allowed to expand along D C, receiving heat from the refrigerator at the lower temperature and rejecting heat during compression B A at the higher temperature, whilst, on the whole, *work must be supplied to take the heat from the body at the lower temperature.* In this way *the heat motor reversed is a refrigerating machine;* and, according to Carnot, reversibility is the test of a perfect heat engine. The Stirling engine is the first perfect heat engine ever made to work.

Yet the practical difficulties have proved too great, and the best result ever obtained with Stirling's engine is about 2·7 lb. of coal per brake horse-power per hour. That is, less than 7 per cent. of the heat energy given out by the coal in burning appears as useful work done on the brake; whereas, calculation from the range of temperature by the above formula gives as much as 45 per cent. indicated by the ideal diagram. (See Chapter XVI.)

Thus in order that this engine may convert much of the heat into useful work, we require a great range of temperature, that is, a great difference of temperature between the two ends of the large displacer cylinder. Besides, *all* the heat ought to be given to the air at the high limit of temperature. It is very difficult to heat a large volume of air rapidly. To facilitate this process the bottom of the cylinder has been made large and kept very hot, consequently the metal becomes quickly oxidised and the cylinder bottoms get burnt out. The arrangement of the *furnace outside* is very imperfect, a great amount of the heat of combustion of the fuel being lost to the surroundings, as well as by the resistances to its passage, from the furnace outside to the air inside the displacer cylinder. These defects and difficulties have prevented the general adoption of this engine in practice, though the principle on which it is designed is good, in fact, theoretically perfect.

The ROBINSON hot-air engine, Fig. 82, is a small form of the Stirling type, made by Messrs. Frank Pearn & Co., of Manchester, until a few years ago.

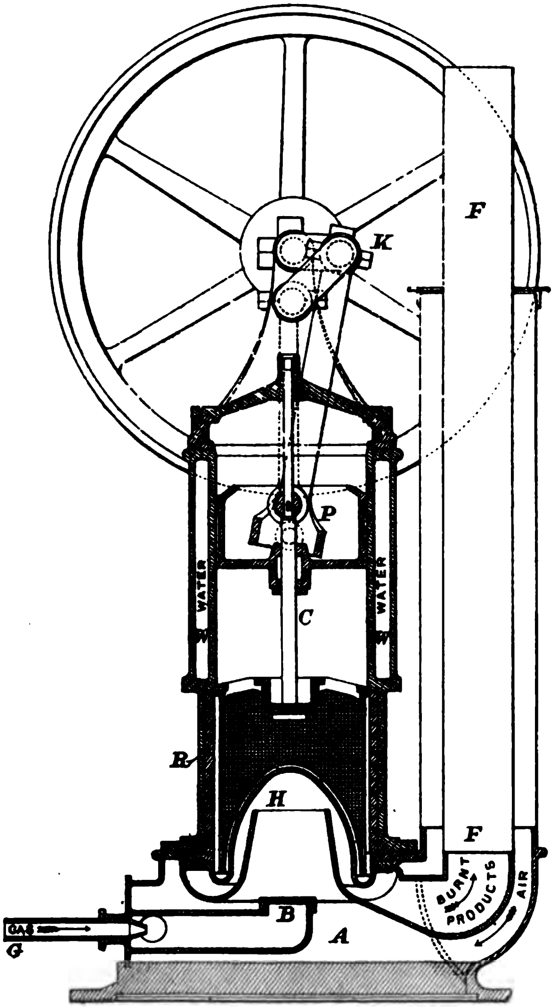
In the cylinder C there is the working piston P, attached by a connecting rod to a crank K on the driving shaft, whilst a second crank, fixed 90° in advance, and a rod through P, works the displacer D, which contains a network of wire gauze acting as *regenerator*. This arrangement, with piston and displacer in one line, is very compact.

The upper part of the cylinder is the *refrigerator*, surrounded by a cold water-jacket W; but the lower or hot part is lined with non-conducting refractory material, as fire-brick, R.

The cylinder is closed at the bottom by a dome-shaped plate H; gas enters through G to the Bunsen burner B, and the products of combustion pass up the chimney F, surrounded by a casing through which air is drawn into the space A to supply the burner. The combustion is complete, and the waste heat is utilised to warm the incoming air.

The action depends upon the alternate expansion and contraction produced by the heating and cooling of the same mass of air. As the displacer D is moved upwards from its lowest position, the cold air from C passes through the wire gauze, from which it receives heat, and when D is in its highest position, most of the heated air is exposed to the action of the furnace through the metal plate H. The air, when heated, increases in pressure, expands, and raises the piston P. As D moves downwards again, the hot air is passed up through

FIG. 82.

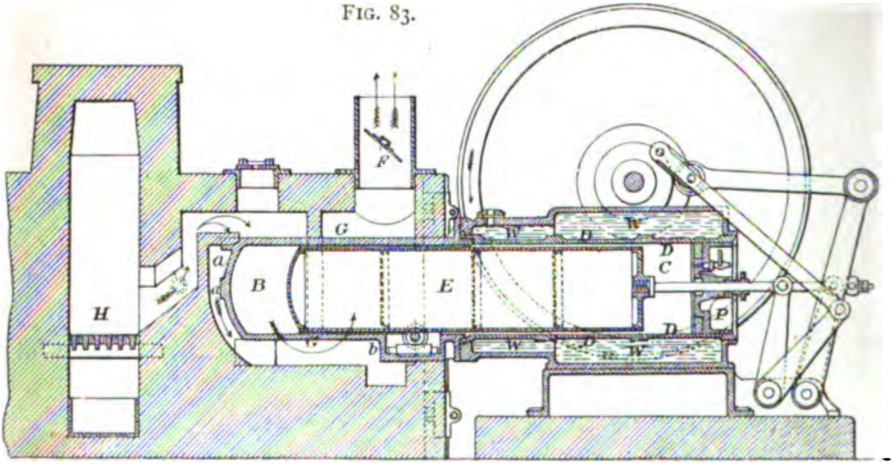


ROBINSON'S HOT-AIR ENGINE.

the regenerator, to which it gives heat, and is still further cooled by the water-jacket W; therefore the pressure diminishes, the air in C contracts, and the piston P descends. When P comes near the lowest part of its stroke, D begins to rise, and as the cool air is passed down through the regenerator, heat is restored to the air before it is again exposed to the furnace. Thus heat is supplied to the hot air at its highest temperature; then as the air passes up through the regenerator, it becomes cooled and loses heat to the refrigerator when at the lowest temperature. This is the condition aimed at in an ideal perfect heat engine.

The parts of this engine are few and simple, but the great drawback is having the furnace outside and the heat transmitted through the metal plate or bottom H, which gets burnt out and needs frequent renewal. Only very small powers are used. The "two-man" power engine runs at a speed of 270 revolutions, and the cost of gas is about $\frac{7}{8}$*d.* per hour; whilst the "one-man" power costs $\frac{1}{2}$*d.* per hour for gas. This engine has been considerably modified, but cannot compete with the modern gas engine.

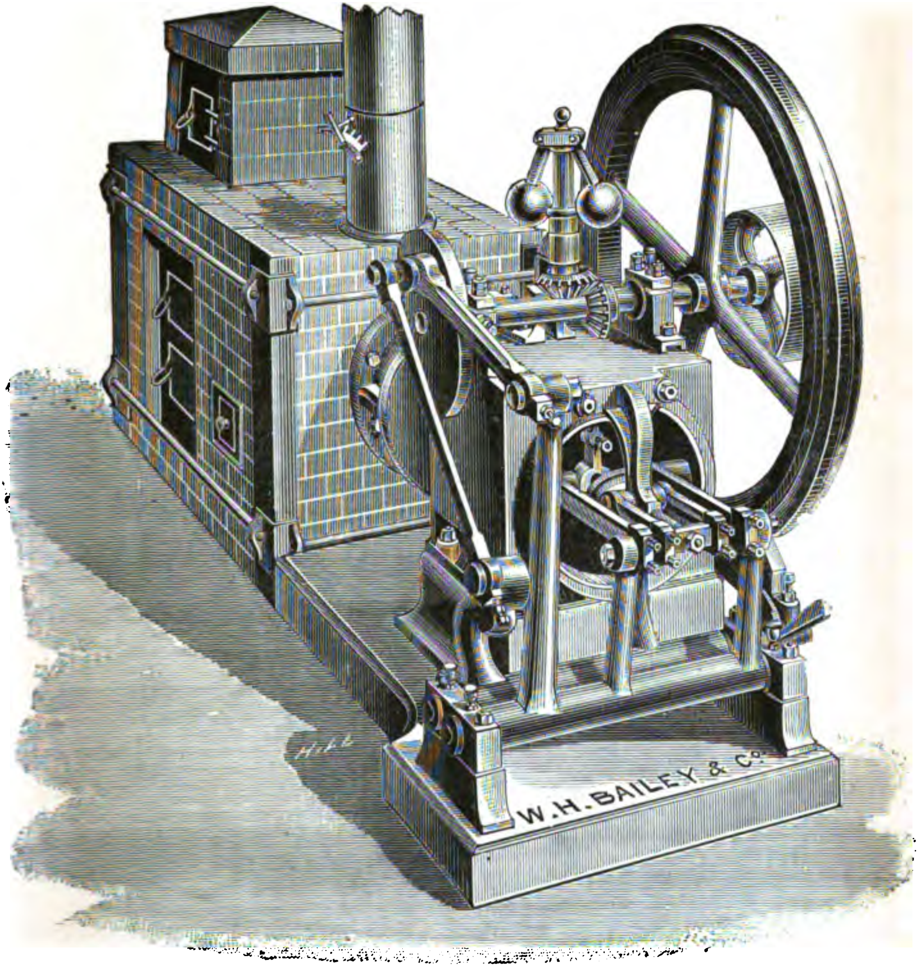
FIG. 83.



*Bailey Hot-air Engine.*

Messrs. W. H. BAILEY & Co., make an engine of the Stirling type, as shown in side view and section, Fig. 83, and perspective, Fig. 84 It consists of a cylinder D, closed at one end by a steel "pot" G, and at the other by the motor piston P, connected by a series of levers to the main crank. This front end of the cylinder is kept cool by a

FIG. 84.


W.H. BAILEY & Co.

BAILEY HOT-AIR ENGINE.

water-jacket W, the steel "pot" at the hot end being built into the furnace. Between the piston P and the bottom of the steel pot is a loose-fitting displacer piston E, with piston-rod passing through the working piston and connected to a secondary crank which is set in advance of the main crank.

The working air is heated in space B between the displacer E and the pot G. The hot products of combustion from the furnace H pass over the fire-bridge and are then divided by the deflector, passing down round the steel pot, through the opening *a*, *b*, under the partition, and out by the flue F. The displacer E is divided internally into compartments by partitions, so that the heat is absorbed by zones varying in temperature, the hottest end being that farthest from the motor piston. This displacer exposes a considerable surface to the working air, which it alternately heats and cools, whilst causing the air to travel backwards and forwards from one end of the cylinder to the other. In fact, the displacer acts as the regenerator in the Stirling engine, storing and restoring heat. As the hot air passes around the displacer from B, it gives up part of its heat to E, and is cooled before it reaches C; it then loses heat when cold. When the air passes back, the heat which it gave up to E is restored before reaching B, where it is heated at the highest temperature. There are no working valves and no exhaust, so that the same air is used continuously; but some air is admitted when the pressure falls below atmospheric.

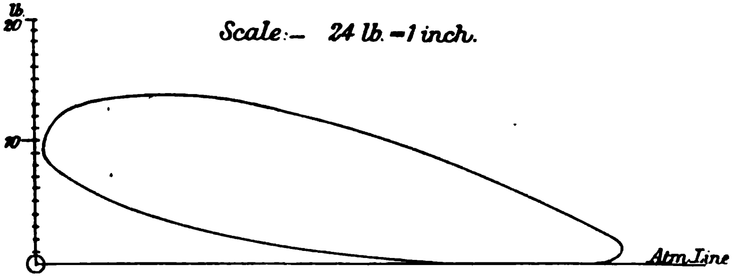
The action is the same as in the Robinson engine.

The indicator diagram, Fig. 85, was taken from an engine nominally of 2 horse-power, driving a dynamo for electric lighting. The average power this size indicates is 4·2 horse-power; the average brake horse-power is 2·6, giving a mechanical efficiency of 62 per cent.

The estimated temperature was 823° Centigrade at the highest pressure, and 373° C. at the atmospheric pressure. The highest pressure attained was 14 lb. per square inch above the atmosphere. The fuel consumption was about

7 lb. of ordinary coal per hour per brake horse-power, and the quantity of cooling water 30 gallons hourly per brake horse-power.

FIG. 85.



INDICATOR DIAGRAM FROM BAILEY'S HOT-AIR ENGINE.

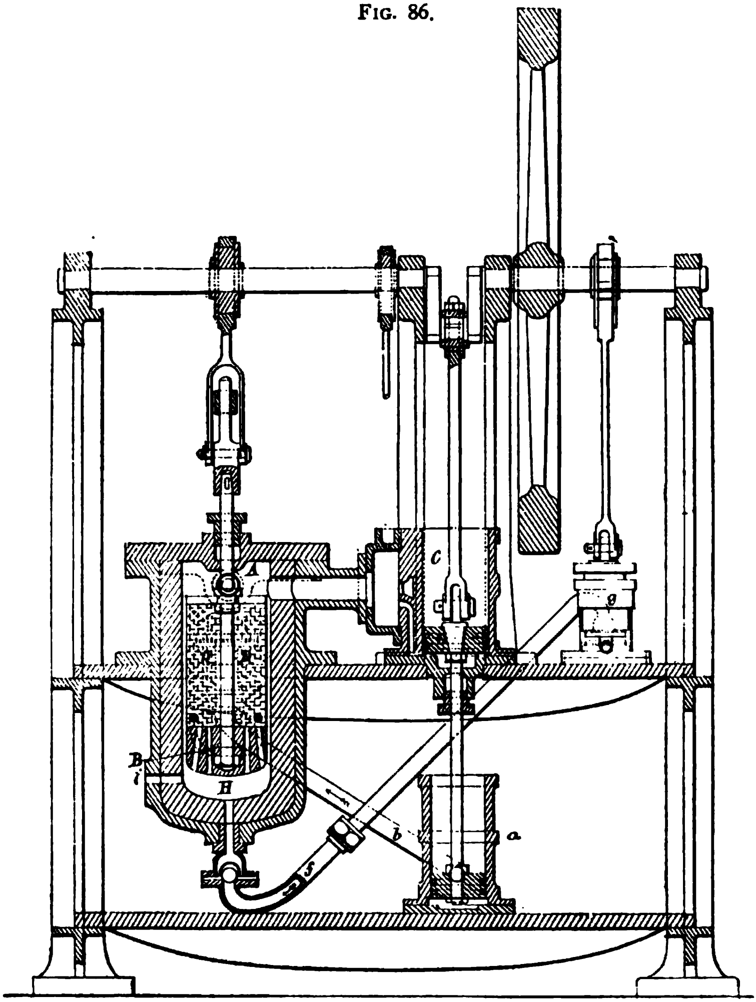
The Bailey hot-air engine is made of sizes from ¼ to 3½ horse-power nominal. This engine requires little oil and attendance, and is employed for small powers only. As in the Robinson engine, the great merit is simplicity, but with the furnace outside there must be great waste of heat by radiation and convection, so that, without force-pumps to get up pressure, these engines can never be used efficiently for large powers. Hot-air engines are being used; but their bulk is enormous when compared with the effective power given out, after deducting that spent by the pump in compressing the air and forcing it through the furnace. However, in slow working the air can be effectually heated, the available mean pressure in the cylinder varying from 2 to 37 lb. per square inch; this means slow production of power for a given amount of plant. If, therefore, we take into account the interest on the price of plant, these engines are expensive as well as cumbersome.

## *Jenkin's Engines.*

Professor FLEEMING JENKIN'S "*fuel engine,*" patented 1874, is based on the same principles as the *Stirling* engine, and its main points can be understood from Fig. 86.

The upper part of the plunger or displacer D contains the regenerator of wire gauze R, between the fire-brick lining B

FIG. 86.



JENKIN'S FUEL ENGINE.

and the cooling chamber A. The combustion chamber H is lined with fire-brick, and being always kept at a white heat, fires the explosive gaseous mixture. In the passage between A and the working cylinder C, there is a slide-valve which regulates the admission of hot gaseous products of combustion to this cylinder.

Separate pumps *a* and *g* are used to compress the air into A, and the fuel into the combustion chamber H; the gas directly by the pipe *f*, and the air pumped by pipe *b* to C and through R.

Air, petroleum, or even comminuted coal dust may be used as fuel, but ordinary coal gas will do.

The working substance is heated at constant volume to high pressure, and then allowed to expand.

The action is as follows:—

The charge of air is pumped into the cooling chamber A, and forced, by the rise of the displacer D, through the regenerator, where it is heated, into the chamber H, where it ignites with the charge of gas or petroleum which has been pumped into H by *g*. The displacer D is now at the top and the piston P near the lower part of its travel. The products of combustion are admitted at high pressure into the working cylinder C, and drive up the piston P, doing useful work. Near the end of this working stroke the valve between C and A opens the passage for the burnt products, which are then driven through the regenerator, giving up their heat to it before they escape into the exhaust or chimney during the return stroke of the working piston P.

A fresh charge of air is again forced into the cooling chamber and goes through the same operation. The ignition port *i* is used until the chamber H is hot enough to start combustion.

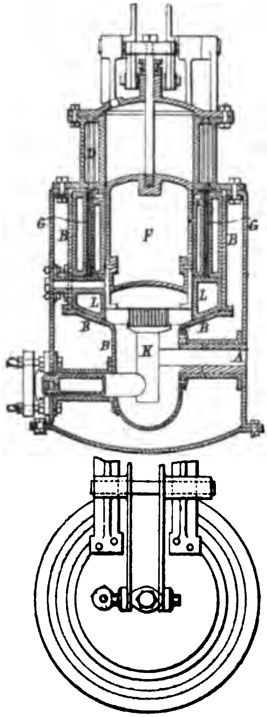
The use of the *regenerator, combined with internal combustion*, is a great step in the right direction, as the latter expedient prevents the waste of heat in its transmission from the fuel across metal plates to the working fluid. However, there are a great many difficulties to be overcome to make such an arrangement practically successful.

Professor FLEEMING JENKIN, assisted by Mr. A. C.

JAMESON, experimented for several years in this line.* It was found that to keep the heat in the combustion chamber and prevent it passing through the sides of the cylinder, an extremely thick lining of refractory material would be required, for small engines as well as for large ones. This means very great loss by radiation, as one would expect; and what is worse, a large amount of clearance or waste space in the engine, owing to the great *porosity* of the fire-clay.

Now increase of clearance space causes the mean effective pressure to fall very considerably, whereas high pressure is necessary to make a Stirling Engine practically efficient. It was found that the fire-clay used for crucibles had 30 per cent. porosity, some fire-bricks as much as 58 per cent., and few less than 30 per cent. The very densest specimen gave 15 per cent. porosity, and 15 per cent. of the volume of this extremely thick lining increased the clearance beyond all management. This difficulty was overcome by putting in a "separator," that is, a metal lining, which separates the great bulk of the outer refractory material from the inner part. The clearance was further diminished by enclosing portions of the refractory non-conducting fire-brick or brickdust in distinct metal casings at the ends of the cylinder.

FIG. 87.



JENKIN AND JAMESON.

Fig. 87 shows a section of the furnace, displacer and regenerator used. The coke is burned at K, and the furnace fired through the opening A. The lower face of the displacer F next the fire has a shield of fire-bricks; it has a metal covering everywhere else. The rods at G act as regenerator. B B is the main separator dividing the spaces filled with refractory non-conducting fire-brick into two portions, the inner having much the smaller capacity. The clearance is also diminished by using distinct casings as at L, filled with non-conducting brick. In this way the clearance was reduced to workable limits. The water-jacket or refrigerator is shown at D.

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* See paper on "Gas and Caloric Engines," read by Professor Fleeming Jenkin before the Institution of Civil Engineers, Session 1883-4.

The valves get burnt out very quickly, so that this engine only reached the experimental stage, and has not been adopted in practice.

Fleeming Jenkin concluded that whereas in the internal-combustion engine of the Stirling type less fuel will be required than in any other, nevertheless, this type of engine is unsuitable for small simple engines, and the larger sizes have yet to be developed.

## EARLY PRACTICAL GAS ENGINES.

### *Dr. Drake's Ignition Engine.*

An engine which bears a close resemblance to the most successful modern gas-engines was exhibited in Philadelphia in 1843, and again with improvements in New York Crystal Palace in the year 1855.* The inventor and exhibitor of this remarkable but now neglected engine was Dr. ALFRED DRAKE, of Philadelphia. He commenced experiments in 1837, and by perseverance and ingenuity brought his machine to a workable form in 1855. Patents: in United States, No. 12715 of April 1855; also in Great Britain, to A. V. Newton, No. 562, 1855.

In external appearance, Dr. Drake's "*ignition engine*" is like a double-acting horizontal steam engine, but a little more bulky for the same power. It has a cylinder 16 inches in diameter, a piston making stroke 18 inches, and connected with a crank shaft, on which there is a heavy fly-wheel. To prevent over-heating and facilitate lubrication, the piston and piston-rod are made hollow, the cylinder is surrounded with a water-jacket, and through all of these a stream of cold water circulates.

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* See *Mechanics' Magazine*, vol. xxxix. Sept. 1843, p. 304; *The Civil Engineer and Architects' Journal*, 1856, vol. xix. p. 340; also *The Artisan*, April 1856, p. 87.

The fuel of this engine is a mixture—one part of ordinary coal or illuminating gas, to 9 or 10 parts of atmospheric air. In order to insure the proper proportion, a regulating valve to the pipe from the supply reservoir and the ignition supply pump, is arranged so as to cover an opening to the gas pipe, and also a much larger opening to the atmosphere. A cock is adjusted to admit only one-tenth of the joint capacity of the openings under the valve, and a mixture is obtained which will produce the most heat, and, consequently, the most power. The power of the engine may be regulated by a throttle valve in the gas supply pipe, controlled by a governor. Petroleum or any volatile hydrocarbon may be used as fuel, by mixing the vapour with suitable proportions of air.

*Mode of Ignition.*—The electric spark being found impracticable, and a jet of gas extinguished at each explosion, the charge is fired by intensely-heated metal igniters. Dr. Drake inserts near each end of the cylinder, at the points where it is intended to fire the charge, a hollow thimble-shaped piece of hard cast iron, 2 or 3 inches long, 1 inch internal diameter, ⅛ inch thick, and directs into the cavity a constant blow-pipe flame from the outside, to keep the metal at a bright white heat. Iron is found to last longer than platinum, but at the best these igniters are liable to crack and get destroyed in a short time by the hot gases.

The *action of the engine* is as follows:—

One part of coal or illuminating gas is mixed with 9 times its bulk of atmospheric air, and the explosive mixture is drawn into the cylinder at the ordinary atmospheric pressure during one-third of the stroke. The valve is then closed, and the piston uncovers an aperture to a small recess in the side of the cylinder, and allows the mixture to be fired by a thimble of iron heated to incandescence. An explosion follows, and the products of combustion instantly expand, exerting a great pressure, of 100 lb. per square inch or upwards, in every direction, and the piston is driven forward, giving motion to machinery.

The engine was designed to be double-acting; but at New York it worked single-acting, the valves at one end of the cylinder being allowed to remain always open to the atmosphere.

The mixed gases, composed of nitrogen, oxygen, and carburetted hydrogen, when ignited in the cylinder, unite chemically, forming carbonic acid, steam, and nitrogen. The products of combustion, when cooled, occupy nearly the same volume as before explosion, so that the great increase in bulk is due to the heat evolved by the rapid combustion.

The pressure on the piston at the moment of explosion has never been accurately tested by indicator; but the engine could work up to 20 horse-power at a speed of 60 revolutions per minute, when single-acting, the mean effective pressure during stroke being 36·5 lb. per square inch. Theory would indicate an absolute pressure of 150 lb. per square inch at the moment of explosion. This is rapidly reduced by the cold water-jacket and metallic enclosure.

The gas employed is from the street mains, the same as used for lighting, but the quantity consumed during any special test is not given. Dr. Drake mixes this gas with pretty nearly its combining weight of oxygen. The explosion is violent, like discharges of artillery; much of the force is suddenly expended on the cylinder heads, and shakes the whole machinery with great violence, so that the action of the engine is unsteady.

These defects do not seem to have been overcome, and although the device attracted some attention, the engine does not appear to have come into common use, and there is no indication of its enthusiastic inventor reaping the pecuniary reward of his labours.

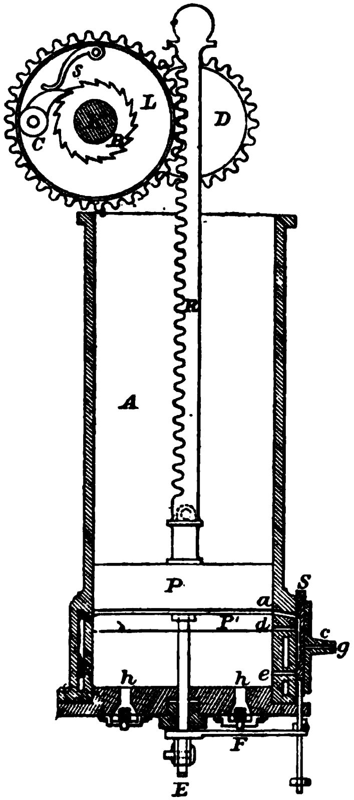
### *Barsanti and Matteucci.*

The next noteworthy invention is that made by EUGENE BARSANTI and FELIX MATTEUCCI. The patent, dated 13th May, 1854, is entitled, "*Mode of Applying the Explosion of Gases as a Motive Power.*" In their patent, 1857, these two Italians describe an ATMOSPHERIC ENGINE with a *free piston*—the *first of this type.* In the first plan, besides the free piston, an auxiliary counter-piston works a slide-valve to draw in the charge of air and gas into the cylinder between the pistons, and drives out the products of combustion. The charge is fired by a series of electric sparks, and the free piston is projected upward, being out of connection with the shaft. The full energy of the explosion is thus expended in doing work, by rapidly driving up the piston, overcoming frictional resistance, its own weight, and the pressure of the external air, until the piston stops. A partial vacuum is formed in the cylinder below the piston by the water-jacket, which rapidly cools the products of combustion, and the piston, being also acted upon by the atmospheric pressure and gravity, begins to descend. It is then made to do the actual work by means of a rack on the piston-rod which gears into a spur-wheel on the fly-wheel shaft; with ratchet and clutch gear to actuate the shaft only during the descent of the piston, and which allows the latter to fly perfectly free during its ascent.

Some idea of this engine may be gathered from Fig. 88, given in the original patent, No. 1655, in 1857. A is the cylinder, open at the upper end and containing the principal working piston P, with rack on the rod R gearing into the spur-wheel L, which runs loose on the main shaft K, but carries the click C, pressed by the spring *s* into the teeth of the ratchet-wheel B, which is keyed on the shaft K. When P moves upwards, the wheel L, carrying *s* and C, turns to the left freely on the shaft K; when P falls, L is turned to the right (clockwise) and, gearing into B, causes the main-shaft K to rotate.

Below the principal piston there is another, the counter-piston P′, with rod E attached by a cross-head to two lever bars (not shown in figure) driven by two eccentrics on adjoining shaft, and which receive their motion from the main-shaft by the wheels D. Thus the counter-piston receives a regular up-and-down movement, so arranged that the downward stroke of the counter-piston P′ cannot take place until the flying-piston P has reached its lowest position.

FIG. 88.



BARSANTI AND MATTEUCCI ENGINE.

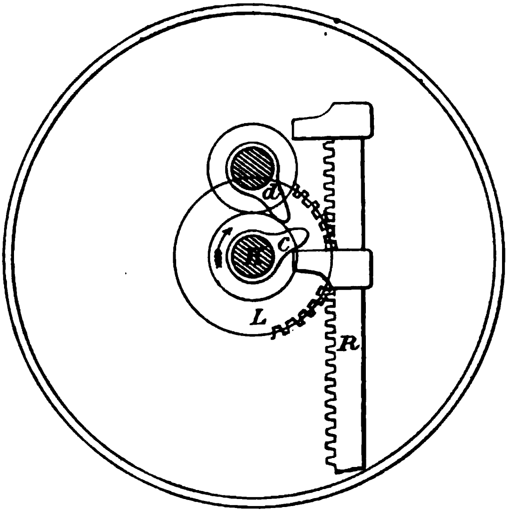
The cover on the lower end of the cylinder is provided with two valves, *h*, *h*, opening upwards. The lever F, attached to the counter piston, actuates the slide valve S, and also closes the electric circuit.

Starting with the *free-piston* P in its lowest position, and the counter-piston P′ in its highest (as in figure), in the first place P′ goes down, and to fill the vacancy between the pistons, air is drawn in through the passages *a*, *b*, and *c*. Soon the arm F moves down the slide S, closing the air port *c*, and opening communication between the gas supply *g* and the cylinder through the ports *d* and *b*. Gas is drawn in between the pistons, until the downward motion of the slide S closes *g* and opens *l*.

At this moment the mixture is ignited by a series of electric sparks, explosion takes place, the piston P is driven upwards free, and the counter-piston clears the bottom of the cylinder through the foot-valves. The water-jacket cools the expanding gases, causing a partial vacuum, when the piston P turns and comes down, driving the main shaft and the fly-wheel, the counter-piston P′ begins its up-stroke and drives out the products of combustion until the port *d* is closed. Then the remaining products between the two pistons are forced out through the passages *a*, *b*, *c*, and the first position is again reached. To obtain uniform motion, two working cylinders are employed, and the pistons act alternately on the same shaft, carrying a fly-wheel of suitable size and weight.

The *second* and simplest form of this engine has a single vertical cylinder, provided with only one motor-piston, like P, free in its upward stroke where projected by an explosion of a gaseous mixture beneath it in the cylinder. The rod R has a rack which works into the toothed wheel L, Fig. 89. K is the motor-shaft, bearing a fly-wheel. A pawl upon the wheel D engages the rachet only on the downstroke of piston, and

FIG. 89.



RACK AND DRIVING GEAR.

drives the motor-shaft, but on the up-stroke it slips on the rachet, so that the shaft revolves continuously in the direction of arrow in Fig. 89. The cams *c* and *d*, operating tappets upon the rack, serve to raise or lower the piston.

The exhaust-valve is at the base of the cylinder. When the products are expelled, the piston is raised a little, so as to draw in a fresh charge of air and gas. The piston next closes the inlet-valves, and the charge is ignited by sparks from a De la Rive multiplier in circuit with a Bunsen battery.

The explosion drives the free piston *rapidly* upwards in the cylinder, and when the whole energy is spent in lifting the piston and the burnt products cooled by the water-jacket, the piston is forced downward, by its own weight and the pressure of the atmosphere, into the partial vacuum, and thus uses the energy stored up in it to drive the motor-shaft.

This atmospheric motor was the forerunner of the well-known Otto and Langen free-piston engine, which it closely resembled in external appearance and mode of working, although the latter was made a practical and commercial success. Why the Barsanti and Matteucci engine did not come into very general use can only be accounted for on the hypothesis that the inventors were not good practical mechanics, and, therefore, unable to apply the discovery they had made. This should teach future inventors the lesson to stick to a good idea and make it a practical success rather than merely resting satisfied with the notion that it is good.

### *Lenoir.*

On the 8th February, 1860, PIERRE LENOIR patented in this country the *first good practical gas motor* that came into general use, and attracted the attention of the industrial and scientific world.

This pioneer gas engine was first manufactured by HIPPOLYTE MARINONI, in Paris, under the Lenoir patent, dated 24th January, 1860, and entitled *Moteur à air dilaté par la combustion du gaz.* These first engines worked fairly well, as they were carefully constructed and finished, but got spoiled by commercial "puffing"—representing the Lenoir as being much better than actual practice showed. Glowing predictions and ludicrous reports were made as to the cost of working in comparison with the steam engine, which was doomed soon to become a thing of the past!

The new motor was even used to propel a boat on the Seine. The Lenoir gas engine craze spread and excited the public. True, the real advantages of this motor were palpable. It could be started or stopped at a moment's notice; it worked pretty steadily without noise or dust, and there was no boiler. It was thus convenient, and suitable for many purposes, especially where small powers were required intermittently. Large numbers were made and sold.

Without any exact idea or proof of the actual cost of working, many persons procured a Lenoir gas engine to whom probably a steam engine would have been better suited.

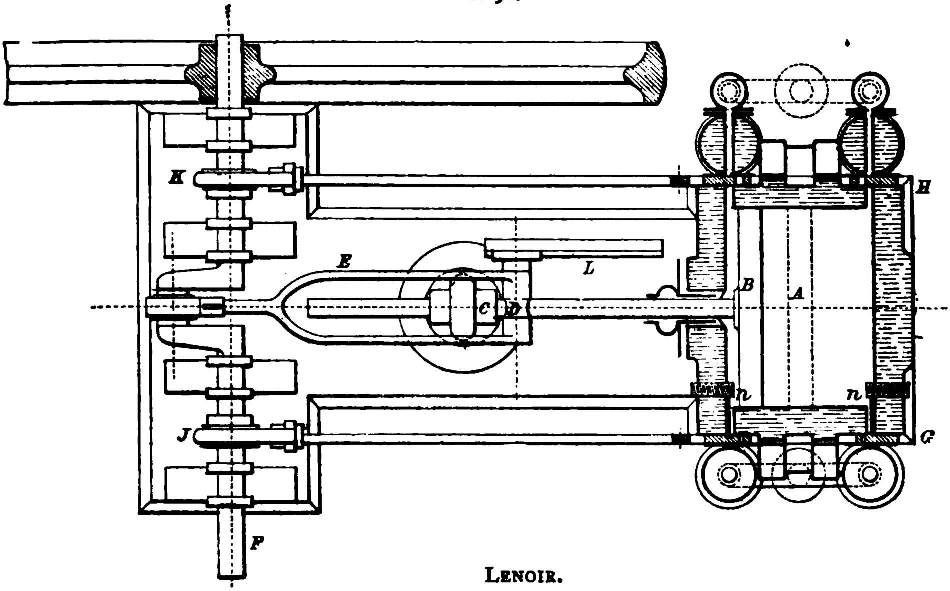
So great became the demand for the new motors that special companies were formed to undertake their mauufacture—one Paris company, and another at Reading, the Reading Iron Works Company, Limited. These engines were not made quite so well. They were found to be noisy; owing to the suddenness of the explosion, they did not work so steadily, and got out of order occasionally; so that, although they did not need a stoker, they did need an oiler. Worst of all, the gas consumption was actually 95 cubic feet, and even as high as 146 cubic feet, of coal gas per indicated horse-power per hour. This excessive and extravagant consumption of gas proved the early statements as to the cost of working to be inaccurate and misleading. The result was that many of these machines fell into complete disuse; the new motor was decried, although several of them have worked well, and are in good condition at the present day.

The engine in the Patent Office, South Kensington Museum, is a good example.

Efforts were made to remedy the defects in design and construction, but before the Lenoir could recover its popularity, the Otto and Langen engine came out, proved to be much more economical, and held the field about ten years.

The LENOIR ENGINE (1860) is horizontal and double-acting, like a high-pressure steam engine. During each stroke of the piston a mixture of gas and air is drawn into the cylinder, alternately on each side of the piston, and ignited, at about half stroke, by the electric spark from a Ruhmkorff induction coil and voltaic battery. The explosion causes a rapid rise of pressure, and forces the piston to the end of the stroke, at the same time expelling from the cylinder the burnt products of previous explosion on the other side of piston. This operation is repeated every stroke, and exhaust takes place exactly as in a double-acting steam engine.

FIG. 90.



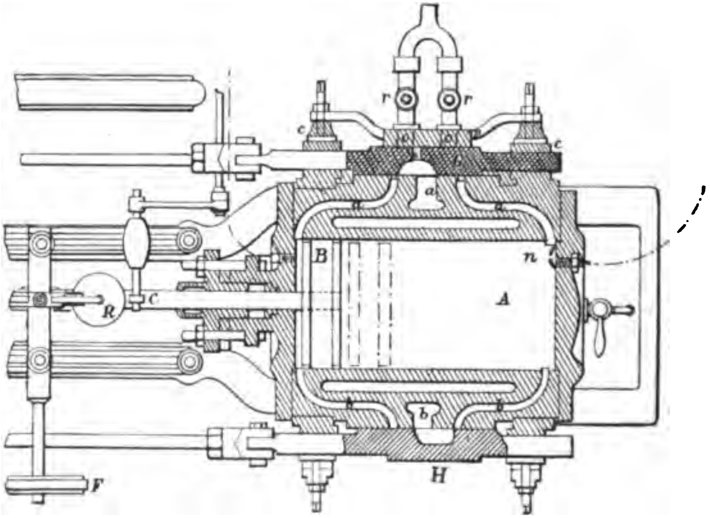
LENOIR.

The sectional plan, Fig. 90, shows in diagrammatic form the general arrangement.

The cylinder A, water-jacketed at every available point, contains the piston B, working the connecting-rod C and the crank-shaft F, connected thereto by the crosshead D and the fork E. The mixture of gas and air is admitted by the inlet slide-valve G, and the products of combustion escape to the exhaust through the outlet-slide H, moved by separate eccentrics J and K respectively. These two slide-valves work between the cylinder faces and covers held by screws against the valve faces.

Fig. 91 represents a partial plan with a horizontal section,

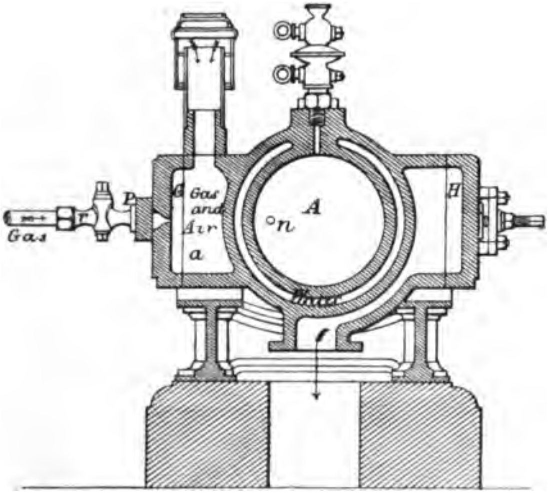
FIG. 91.



HORIZONTAL SECTION.

and Fig. 92 is a transverse vertical section of the working cylinder. The cylinder A, cast with the water-jacket, has two surfaced faces, upon which work the two slide-valves G and H, which open, alternately and at the proper times, the ports for conducting the mixture of air and gas to each side of the piston, as well as the ports for the rejection of the products of combustion. The slide-valve G, which regulates the inlet of the air and gas into the cylinder, is provided with one gas-admission port, which communicates with one or other of the two rows of holes *b*, *c*, Fig. 93, made in the brass plate. This plate carries the two cocks *r*, *r'*, which admit the gas from the forked pipe. The air is admitted through the port *a*, which is in communication with the open

FIG. 92.



WORKING CYLINDER, TRANSVERSE VERTICAL SECTION.

nozzle, surrounded by a cap, as shown in Figs. 91 and 92. The outlet-slide, H, has only two slots, which are brought opposite the cylinder ports at the right time.

The inlet-slide, Fig. 93, is of brass, grooved up at the ends, and pierced with round holes *b*, *c*, through which the gas enters the cylinder from the gas channels.

Fig. 94 is a cross-section, taken through the line of holes opposite either of the two main ports in the cover, showing the larger rectangular passages for the admission of the air between the round gas ports. The gas and air are thoroughly mixed by thus entering the cylinder in numerous separate streams.

This facilitates ignition by the electric spark between the ends of two wires at *n*, Fig. 91. A battery of two Bunsen cells is used, with a Ruhmkorff induction coil and a commutator.

The *electric igniter*, *n n*, placed at each end of the cylinder, consists of a hollow brass plug screwed into the end covers of the cylinder, and having a porcelain or other suitable non-conductor in the form of a short rod fixed inside it. In this rod are placed the wires required to produce the spark; the one wire is in contact with the hollow metal plug, and the other is insulated by the porcelain in the plug, but in electric communication with one of a pair of small insulated plates or segments of a commutator. The positive pole of the battery is in connection with a third insulated segment, whilst the negative pole of the battery is in electric communication with the metal work of the engine. An electric circuit is closed by making contact with one or other of the pair of small insulated plates or segments and the third plate; this is done by a metal slide carried by the crosshead of the piston-rod, kept in contact with both plates. The segments are adjusted so that the electric spark from the induction coil passes between the platinum points at either end of the cylinder, just as the gas admission valve closes at that end. When a short circuit occurs to cause a miss-fire or late ignition, the platinum points of the igniters must be cleaned and dried. This is the weak point which gives trouble in practice.

FIG. 93.

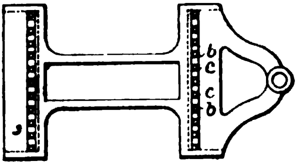
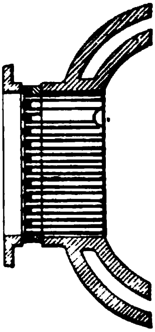


FIG. 94.



(ELEVATION.) ADMISSION SLIDE. (SECTION.)

As the action of the flywheel drives the piston forward from its position in Fig. 91, it draws in a charge of air and gas in the proportion of about 12 to 1. The air port opens to the cylinder before the piston completes its previous stroke, and after that the gas port opens. The gas supply is regulated by a throttle-valve and governor. The inlet slide G closes when the piston has travelled half the length of its stroke, causing the pressure behind the piston to fall slightly below that of the atmosphere. The mixture is then fired by a series of electric sparks; the pressure suddenly rises to between five and six atmospheres. The water-jacket has cooled the products of the previous combustion in the cylinder before the piston; and these are driven out, when the exhaust port H opens, at a pressure of about 1·5 atmosphere.

During the return stroke, a mixture of air and gas is drawn in through G, behind the piston, ignited at half stroke, and, as before, the burnt products on the other side of the piston are expelled into the exhaust at a temperature of 600° to 800° C.

The engine works best running slowly, with a piston velocity of about 2·7 feet per second; and the gas consumption, according to Tresca, is 95 cubic feet per indicated horse-power per hour. Only 4 per cent. of the whole heat generated is converted into useful work, 66 per cent. of the total heat is taken away by the water surrounding the cylinder, whilst of the remaining 30 per cent., part escapes with the discharged products of combustion, and the rest is lost in shocks, friction, conduction, and radiation.

Indicator diagrams of the Lenoir engine are shown in Figs. 95 and 96.*

The mode of firing the charge was unreliable, irregular, and defective. Sometimes the electric spark failed to explode the mixture; and the late ignitions in Fig. 96 were caused by the insulated points of the wires getting wet, the water film completing the circuit for the electric current between the wires, and thus preventing the passage of the spark.

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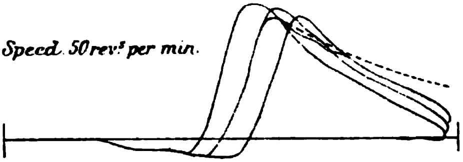
* *Journal of the Franklin Institute*, vol. lxxxi. (1886), p. 175. 'The Lenoir Gas Engine,' by Fred. I. Slade.

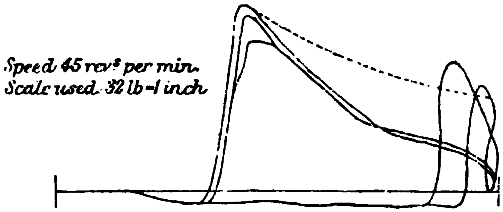
Mr. Slade gives the maximum temperature after ignition at about 1356° C., and says: "The dotted lines represent the theoretical curve of expansion, taking into account the loss of heat and consequent fall of pressure, due to the work done (which is the proper theoretical curve for an indicated diagram). The temperature at the end of the stroke, indicated by this line, would be 1180° C. The final temperature shown by the diagram, supposing no leakage, is 781° C."

Fig. 95.



Indicator Diagrams from Lenoir.

Fig. 96.



Cards from Lenoir Engine.

Serious trouble in working arose from overheating of the cylinder and piston. The expansion of the working parts on heating prevented them being air-tight when cool, and rendered delicate adjustment of the slides difficult. The cylinder was liable to be scored and cut up, owing to heating, unless a large quantity of water was kept flowing round the water-jacket, and even then the piston soon became unduly heated. Besides, the cylinder and ports required daily cleaning.

Owing to the great cooling effect of the water-jacket surrounding the cylinder, one would naturally expect the expansion curves to fall more rapidly below this adiabatic line.

The sustained pressure, keeping up the expansion curves, is evidently due to the evolution of heat whilst the piston is moving. This clearly points to dissociation after the explosion, followed by re-combination of the gases as the piston advances and the temperature falls.

As the piston travels at a comparatively slow pace, the explosion and consequent expansion of the gases cause a sudden force on the piston, more of the nature of a blow than of a steady pressure. The inventor tried to remedy this apparent defect, by admitting the air and gas in a stratified form, in order to obtain slower combustion and have a less sudden but better sustained pressure.

In his patent specification of 14th January, 1861, Lenoir proposes to inject *a little steam or moist vapour into the cylinder* at the same time that the "*air and gas enter and remain in the cylinder in regular strata or layers.*" Not only does the moist vapour take up part of the heat generated by the explosion, and by evaporation aid in the expansion, at the same time keeping the working parts cool and acting as a lubricant, but the presence of a little steam also greatly assists the chemical combination of an explosive mixture, and makes the explosion certain.

The erroneous idea was, by stratification and steam injection to avoid sudden explosion, and thereby improve the economy, "increasing the effect of the engine."

In the same year, 1861, GUSTAV SCHMIDT pointed out that the real cause of uneconomical working was want of compression of the cold gases before combustion. In a paper on the "Theory of the Lenoir Gas Motor," he says:—"The results would be much more favourable if compression pumps, worked by the engine, compressed the cold air and cold gas to three atmospheres before entering the cylinder, by which a far greater expansion and advantage by transformation of the heat of combustion would be possible."

Compression of the explosive mixture before ignition had been used by Lebon in his engine of 1799.

Then in 1858 and 1859 DE GRAND fully described, amongst others, a four-cycle compression engine, but the mechanical details were not practical.

However, in another patent, No. 1840, of the year 1861, MILLION clearly points out the advantages of compression in securing sudden ignition of the gases in the motor cylinder, whilst the high pressure at which the work is done enables the engine to exert great power in proportion to its dimensions. He proposes to make the motor cylinder longer than necessary, in order that the piston should leave between it and the end of the cylinder a space called a *cartridge*, in which the gases are compressed before ignition.

Also in 1862, BEAU DE ROCHAS, both in his patent specification and pamphlet, lays down the conditions necessary to realise the most economical results in the compression gas engine as given above at page 34. He fully describes the four-cycle mode of working with compression, which, subsequently, in 1876, became a practical success in the hands of Dr. Otto in the "Otto Silent" Engine, and was used by Lenoir in his later engine of 1883 (see page 174).

### *Hugon.*

About this time, PIERRE HUGON, director of the Parisian gasworks, was doing his utmost to obtain motive power by the explosion of a mixture of air and gas.

He observed that, in direct action engines, the shock produced by the sudden expansion of the explosive gaseous mixture when fired, being directly transmitted to the moving parts, formed a difficulty in its application; and he was led to design an engine of indirect action.

His first attempt, in 1860, was somewhat on the same lines as Brown's for raising water. He had a large U tube nearly filled with water, one limb being closed at the top, the other provided with valves and communicating with a cylinder and motor piston. The mixture was exploded at the top of one of the arms, driving the column of water up the other arm and part of it through a valve which closed automatically as soon as the energy of the explosion was expended. The sudden contraction of the burnt products coming in contact with the water, never above 45° C., produced a partial vacuum, and a fresh column of water, forced by the reaction pressure into the tube through a cylinder, moved the motor piston.

In 1863, he tried to utilise both the energy of the explosion and the vacuum produced, by driving the water from one tube against one side of the piston, while the vacuum formed by condensation in another tube was drawing the water from the other side of the piston; when the piston was thus driven from one end of the cylinder to the other, the position would be reversed, and the same column of water would always be passing in and out of the cylinder. Water was in every part of the engine.

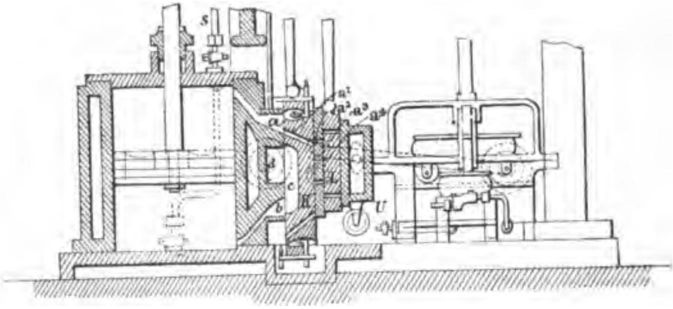
He proposed to ignite the explosive mixture, either by an electric spark, an incandescent platinum wire, or a gas flame, by means of a slide which advances to inflame the mixture through an orifice, and then recedes to have its jet relighted, the explosion having extinguished it. Though he laboured long at such engines, he does not appear to have obtained any satisfactory results.

In 1865, HUGON patented a direct working and practical engine of the vertical type, with an ordinary cylinder and piston, double-acting, and in principle very like the Lenoir, with the important improvement of a flame ignition instead of the electric spark.

Hugon used a slide valve carrying two burners, supplied with gas under slight pressure, each lighted by a gas jet kept constantly burning outside the cylinder, to bring the flame opposite the cylinder ports, and explode the charge at the proper time.

Another distinguishing feature was *the injection of water into the cylinder to cool it.* This water absorbed part of the heat suddenly generated by the explosion, protected the cylinder and piston from over-heating, and moderated the violence of the action; whilst, being changed into steam, it aided the expansion and sustained the pressure better during the stroke, thus effecting a decided economy in both the oil and gas consumption.

FIG. 97.



HUGON'S ENGINE, 1865.

Fig. 97 is a sectional elevation showing only the piston and valve arrangement in this Hugon engine. The action is as follows :* As the piston is lowered, it draws in above it an explosive charge from the mixing chamber U, fed by the bellows pump or by a caoutchouc bag ; at the same time that it expels the products of the previous combustion from the lower part of the cylinder by *b*, *c*, *d*, as in the steam engine exhaust. When the piston has travelled about 0·4 of its course, the principal slide K descends and shuts the communications $a_1$ $a_2$ $a_3$ $a_4$ between the admission port *a* and the mixing chamber U ; at the same time the igniting flame, from the upper burner carried in the slide, is projected into *a*, and causes the explosion. The same operations occur on the other side of the piston in its ascent.

It will be observed that the distribution is effected by two slides : the inner one, K, serving for admission, exhaust, and ignition ; the outer slide, L, suddenly actuated by a cam, controlling the supply of the explosive mixture from the chamber U, so as to secure a rapid opening of the communication for admission of the mixture, as well as a rapid cut-off at the proper time, just as the igniting port in K brings the flame to fire the charge.

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* French Patent, No. 66,807, 29th March, 1865.

During each stroke a pump injects a small quantity of water spray into the cylinder through S, at the instant of explosion, for the purpose of reducing its violence and cooling the cylinder.

In order that the feed may not be affected by the varying pressure in the gas main, the air and gas are mixed in a fixed indiarubber bellows pump. A smaller bellows pump supplies the reservoir which feeds the four ignition flames. It can be moved by hand to ignite the flame before starting the engine, and this is done by turning the fly-wheel. The rubber bellows gave trouble by leakage, and in some cases were replaced by metal pumps with mixing valve.

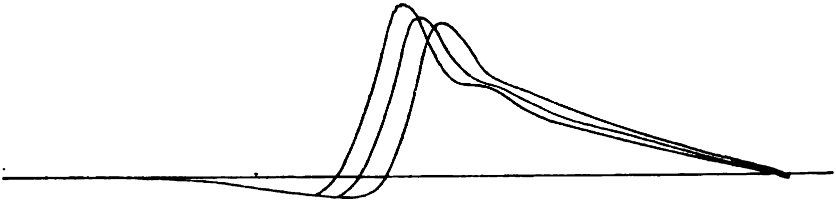
Hugon also designed a horizontal type, as described (French patent, No. 117,390, of 7th March, 1877), being the final form adopted in practice. The Hugon engine was exhibited and sold in considerable numbers in and about London. A small one (½ H.P.) may still be seen in the Patent Office Museum, South Kensington.

The Hugon was decidedly an improvement on the Lenoir. In it we have the first successful application of the ignition slide mode of firing, so extensively used up to the present time. The flame ignition gave certainty of action, and the water injection kept the cylinder and piston cool, even during a day's continuous run, the engine doing heavy work smoothly and with great regularity. The slide valve arrangement was ingenious but complicated; the ports were liable to get stopped easily, and required frequent cleaning.

The indicator card, Fig. 98, shows how closely the cycle of operations agrees with the Lenoir. With the flame ignition weaker mixtures can be used, hence the retarded explosion and more prolonged expansion, although great economy could not be expected without compression.

Trials of the Hugon motor by Professor Tresca, at Paris, in 1866, gave the following figures:—During a 5 hours' run, speed 53 revolutions per minute, maximum pressure 3·27 atmospheres, with mixture 1 vol. of gas to 13 vols. air; temperature of exhaust gases 186° C., temperature of water-jacket 42° C.; giving out 2·07 brake horse-power with a gas consumptionat the rate of 92 cubic feet per hour per horse-power.

FIG. 98.



HUGON DIAGRAM AT 60 REVOLUTIONS, 1 INCH = 32 LB.

Some results have been obtained with this engine showing a gas consumption of 74 cubic feet per indicated horse-power per hour. An engine of 12·75 inches stroke worked with a piston velocity 1·8 feet per second, and had mechanical efficiency 0·58. The mixture of air and gas was in the proportion 13·5 : 1, the maximum pressure 3·8 atmospheres, and the gases escaped at 190.° C.

### *Siemens' Early Engines.*

So early as 1860 Sir WILLIAM SIEMENS had elaborately * worked at the idea of *adapting the regenerator to the internal combustion engine.*

In his hot-cylinder engine, water-gas and air are pumped into a reservoir under pressure, then by a rotatory distributing valve through a regenerator, where they are mixed and highly heated before passing into the working cylinders. The compressed mixture is ignited as it enters each working cylinder, without rise of pressure. At first the burning gases expand at constant pressure, driving forward each working piston through half its stroke, and the second half is effected by the adiabatic expansion of the hot gases to double their volume. The products of combustion, after having thus served to propel the working piston by their expansive action, are discharged through a regenerator, giving up a large portion of their heat, which is available for heating the next fresh charge of incoming gases passing through the regenerator before combustion takes place.

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* Patents, No. 12,531, 20th March, 1849; No. 2074, 28th August, 1860; No. 2143, 28th July, 1862. See also the patents 12,006 (1846), 12,531 (1849), 326 (1852), 1363 (1856), 2246 (1873), 2504 and 5350 (1881).

In the gas *generator*, steam and heated air under pressure are passed through incandescent fuel, forming water-gas—a mixture of hydrogen, carbonic oxide, carbonic acid, and nitrogen—used to supply the engine.

A central cylinder constitutes the reservoir for the compressed combustible gases. The working cylinders $C_1$, $C_2$, $C_3$, $C_4$, are of the same diameter, whilst their continuations $E_1$, $E_2$, $E_3$, $E_4$ contain small vessels filled with layers of metallic gauze, which are the regenerators, $R_1$, $R_2$, $R_3$, and $R_4$, of the engine. There is communication between the back of $E_1$ and the front of $C_2$ through the regenerator $R_1$, also between the back of $E_2$ and the front of $C_3$, the back of $E_3$ and the front of $C_4$, and, lastly, between the back of $E_4$ and the front of $C_1$, thus completing the circle. In this way the front part of one cylinder answers the purpose of charging cylinder to the next, and so on.

A continuous flow of water is kept up round the cylinders.

The working pistons are attached by hollow piston-rods to an oscillating disk, at points 90 degrees apart from each other, so that the reciprocating motion they give to the disk is converted into rotatory motion of the main shaft carrying a heavy fly-wheel.

In 1862, SIEMENS patented an improved form of his early engine. As before, the combustible gases and air are compressed and forced by means of a pump into a strong receiver or reservoir in such proportions as to make a combustible mixture. The pressure maintained in the reservoir should exceed the working pressure to be attained in the combustion chamber connected with the working cylinder.

Combustible petroleum vapour or cheap producer gas may be used.

A small quantity of the explosive gaseous mixture is first allowed into a passage, formed in refractory material, where the gases are united and continue to burn, and whence the flame issues into the combustion chamber, firing greater volumes of the mixture.

He lines with refractory materials that portion of the chamber in which the gases burn, and the working cylinders where the heated products enter, as well as protecting those parts of the working pistons which come into contact with the flames.

The whole of the products of combustion, after having served to propel the working pistons, are discharged into the atmosphere through a regenerator chamber filled with metal or other good conductor of heat presenting a *large surface for the absorption of the heat* from the gases. The combustible gases and air required to effect the next working stroke are passed in the opposite direction through the same regenerator, in order that they may take up the heat there deposited before they are ignited.

Sometimes water is admitted with the gases into the pumping cylinder to cool and lubricate it, as well as to form vapour of water, which it is found enhances the effect of the gases in combustion.

The valves, pumps, and other working cylinders of the engine are surrounded with water to keep them cool.

In 1862 Siemens exhibited a model engine with two working pistons attached to cranks at 180°, and was *awarded a medal.** None of Siemens' engines have ever come into practical use, nor have any of the actual results obtained from his trials of them been laid before the public, although several large engines of this type have been built. He states that this engine promised to give very good results (see modifications, page 203), but about that time he turned his attention to and spent his life-work mainly in adapting the regenerator to the furnace and metallurgic processes.

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* *The Practical Mechanics' Journal*, September 1862.

## *Otto and Langen.*

Meanwhile two Germans—OTTO AND LANGEN—were working with unwearied activity, and had discovered a most economic and practical solution of the problem: to obtain motive power from a gaseous mixture. Their idea was to avoid at least some of the effects resulting from the shock of the sudden explosion by first storing up the energy without allowing it to act directly upon the machinery, and then to utilise it as well as the partial vacuum that would follow.

In 1863 Otto patented an engine embodying this principle and the free flying piston. It was of the vertical type. The cylinder, open at the top, contained two pistons. One was hollow, with holes through it, and a valve on the upper side. The piston rod was also hollow, and inside it fitted and worked the rod of a solid piston.

When both pistons are at the bottom of the cylinder, if the crank shaft is made to revolve, the hollow piston is raised nearly to the full extent of its stroke, without raising the solid piston, whilst air is admitted through a valve between the two pistons. Then the air passage is closed, and a catch on the end of the rod begins to lift the solid piston, which, acting as an exhauster, draws in beneath it a charge of gas and air. The mixture is fired electrically, and the force of the expanding gases drives the solid piston freely and rapidly to the top of its stroke, forcing the air out through the valves and holes in the hollow piston. The water-jacket cools the gaseous products, causing condensation and partial vacuum, and the atmospheric pressure acting on the upper side, together with gravity, both pistons descend slowly together to the bottom of the cylinder, doing work and expelling the burnt gases. The momentum of the fly-wheel again lifts the hollow piston as before. An obvious difficulty is to have the strength of the charge always the same, so as to throw up the piston the proper distance, and no further, at the risk of knocking against the hollow cylinder, though the energy of the explosion is then nearly spent, so that the shock cannot be violent.

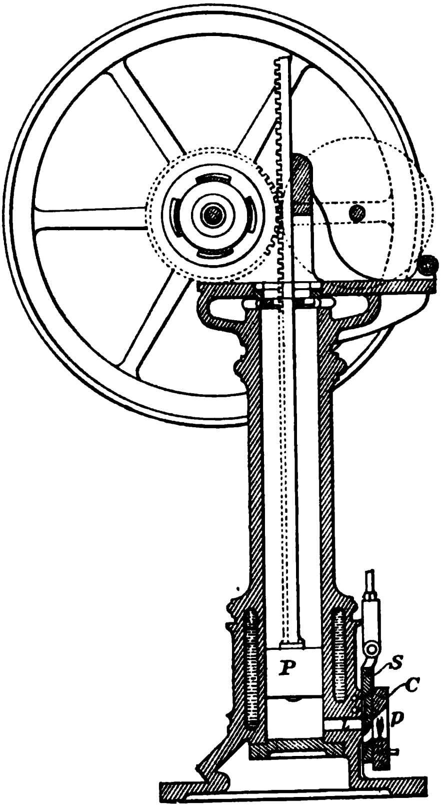
Whilst designing the free piston engine these inventors were guided by the following considerations tersely put in their patent: "In igniting combustible gases inside a closed metallic vessel, the heat generated is imparted to the gaseous products of combustion, which, if prevented from expanding in consequence of increased temperature, will exert a proportionate pressure upon the inner surface of the closed vessel. This pressure would remain constant if no heat were taken away from the gases, but it will in reality diminish rapidly in consequence of the heat generated being absorbed by the metallic surfaces of the vessel. Experience has shown that the interval of time which elapses between the heating and consequent expanding of the gases, and the subsequent cooling and consequent contraction, is but a very short one, and therefore, in applying the expansive force of such heated gases as motive power, unless they are allowed to expand very rapidly—immediately after combustion has taken place—a great portion of the heat which should have produced such expansion will be absorbed by the cylinder of the engine, and, consequently, a great portion of the motive power will be lost."

Hence they very properly arrange to make the explosion and expansion of the gases take place with great rapidity, so as to allow very little time for heat to be given out to the cylinder walls, whilst the gases are cooled rapidly by the great expansion, and the heat-energy is mainly expended in throwing up the piston and rack like a projectile.

After the pressure of the burning gases in the cylinder has fallen to atmospheric, the energy of motion is spent in carrying the piston still higher in its flight, pushing back the atmosphere. This prolonged expansion of the burnt products, and the cooling action of the water-jacket, together form a partial vacuum in the cylinder which allows the piston to fall, under the action of gravity and atmospheric pressure, spending the energy of the explosion slowly in doing work.

In 1866, these ideas assumed a practical form—the famous OTTO AND LANGEN *atmospheric and free piston engine*, which was made known to the world through the Paris Exposition of 1867. The machine was identical in principle and the same in general construction as that invented ten years earlier by Barsanti and Matteucci, but the details were worked out so completely as to attract attention by the noisy, irregular action, and at the same time to work with far greater economy than any previous form of prime motor. This free piston engine of strange appearance, necessarily bulky for its small power, and somewhat resembling a pile-driver in action,

FIG. 99.



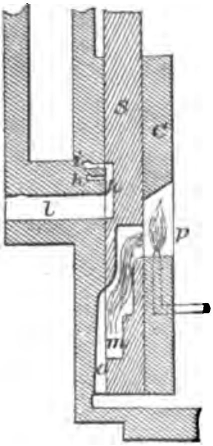
OTTO AND LANGEN ENGINE.

was made a practical commercial success by its ingenious *clutch gear*, *flame ignition*, and *centrifugal governor*.

Here we have a very tall vertical cylinder open at the top and containing one piston, whose rod has teeth gearing into a spur-wheel on the fly-wheel shaft, driving it by means of clutch gear only during the downstroke. The piston is thrown up by the explosion, the toothed wheel running perfectly free on the shaft. A small auxiliary shaft, thrown into gear with the main shaft by a ratchet and pawl worked by the governor lever, actuates the slide valve which admits the charge below the piston, carries a gas flame to fire it at the proper time, and allows the burnt products to escape.

In 1867 improvements were made in the spur wheel to work on the driving shaft and in the coupling or clutch gear, to give greater freedom of action during the ascent, and greater certainty of gearing without backlash during the descent of the piston, as well as in the arrangement of eccentrics and levers on the shaft to regulate the slide-valve movement and to lift the piston while it is sucking in the charge. The construction of the distributing slide S, with ignition chamber, is seen by Fig. 100. This slide is worked from the small auxiliary shaft by the rod (shown broken) and is pressed against the valve-face by the slide cover C and spiral springs under the nuts of its fastening screws. The charge of gas enters by the passage *h*, the air by *i* through the slide cavity *k* and the passage *l* below the piston. When the slide S is in its lowest position, a mixture of gas and air flows into the chamber *m* through the passage *o*, and is ignited by the gas-flame *p* in the slide-cover. Now as the slide moves up, this lighting port *m* is closed, and carries the burning mixture opposite *l*, when a tongue of flame, shooting through *l*, fires the mixture in the cylinder.

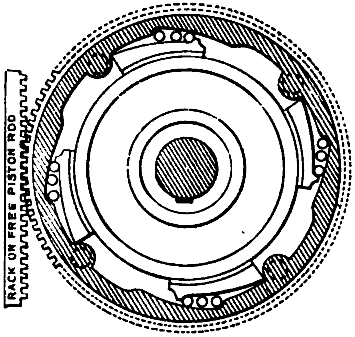
FIG. 100



SLIDE-VALVE.

The clutch or coupling gear, shown in elevation, Fig. 101, is the chief feature of the invention. The inner central part is rigidly keyed to the main shaft. Around this is a double disk, shown shaded, gearing into the piston-rod rack. Between this outer disk and the inner rim there are four wedge-shaped steel pieces, on each of which three rollers run freely while the rack moves upward, so that the outer disk then runs loose, and in the opposite direction to the main shaft. On the other hand, when the piston and rack move down, the rollers are wedged between the steel pieces and the inner inclined surfaces of the shaded disk, thus locking together the toothed part with the inner one keyed on the motor shaft. Hence in its downward stroke the piston drives the motor shaft with fly-wheel. On the return upward stroke of piston and rack the rollers loosen the wedges so that the part with the teeth again runs loose.

Fig. 101.



Otto and Langen Clutch.

The action of the engine is as follows :—

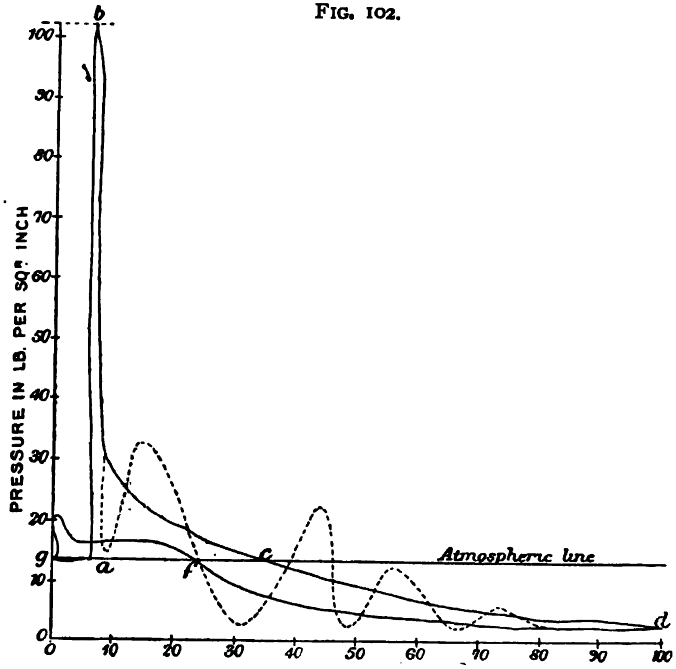
In the first place, the momentum of the fly-wheel lifts the piston, sucking in, at a little under atmospheric pressure, a charge of gas and air, from *h* and *i* through the slide *k* and passage *l*. When this admission port *l* is closed by the slide, the charge is fired by the intermediate flame *m*, and the piston, with its rack gearing into the toothed disk, running free and loose on the main shaft, is thrown up with great velocity, being gradually brought to rest by gravity and by the atmospheric pressure. The pressure below the piston falls in consequence of the cooling of the gases by the great and rapid expansion and by the water-jacket.

After the piston reaches the highest point of its flight, it falls down by reason of the atmospheric pressure and its own weight, whilst it drives the main shaft and does useful work. The back pressure in the cylinder below the piston, at first about ¼ atmosphere, gradually rises by compression to one atmosphere. Now the piston drives out the burnt gases, whilst it sinks further down by its own weight.

The energy stored up in the fly-wheel again lifts the piston, and the same cycle is gone through.

The indicator diagram, Fig. 102, published by Mr. F. W. Crossley, enables us readily to follow the action throughout.

FIG. 102.



Percentage of Stroke.

OTTO AND LANGEN ENGINE (FREE PISTON).

There are thus three operations :

1, *g a.* Admission of the charge of gas and air.

2, *a b.* Explosion at almost constant volume because of the heavy weight of piston, followed by expansion *b c d*; the piston being suddenly projected upwards by the expanding gases until the whole energy of motion is spent. The sudden explosion causes so great vibration of the indicator pencil, that the line *b c d* can only give a vague idea of the pressure.

3, *d f g*. Downstroke of the piston doing work by means of the atmospheric pressure and of gravity opposed by the back pressure, followed by discharge of the cooled products.

It will be observed that the negative work represented by area *f g a f*, corresponding to discharge of products and drawing in fresh charge, is relatively very small. The charge consists of one volume of coal-gas to nine volumes of air; the pressure rises to four or five atmospheres, and the energy of the explosion is so quickly expended in giving the piston potential energy, that very little heat is given out to the cylinder. This, together with the very long expansion, to more than ten times its original volume, explains the high efficiency of these motors. In fact, the Otto and Langen worked much more economically than any previous engine.

For small powers (about ½ horse-power) the gas consumption at the beginning was about 44 cubic feet per hour per brake horse-power, which was reduced by improvements in the three-horse engine to 30 cubic feet per brake horse-power per hour. It is more satisfactory to know the consumption per brake or actual horse-power, for it is not clear how the indicated horse-power could be accurately calculated from the diagrams, since the mean pressure can only be vague and uncertain, owing to the vibrations of the indicator spring. However, it is certain this prime motor used less gas than the Lenoir and Hugon motors, and proved to be practically useful for small industries and for domestic requirements. Otto and Langen pushed forward their motors; the German firm at Deutz constructed and sold more than 5000 in about ten years.

This engine was not without some serious *drawbacks*. The rack and wheels made a great noise during the upstroke of the piston; and this noisy action was rendered very unpleasant to the ear by being quite irregular. As regards construction, the mechanism was difficult and complicated, not favourable for durability, whilst the whole arrangement was heavy and cumbersome. The velocity could not exceed 35 revolutions per minute without danger to the moving parts and the noise becoming intolerable. When the piston made 28 strokes per minute, the temperature of the exhaust gases was about 180° C.; and if a reservoir containing 70 cubic feet of water was used for cooling the cylinder, and the temperature of the water 15° C. at the beginning, after ten hours' continuous working it entered the water-jacket at 67° C. and left at 83° C. Only small sizes of this engine could be made, because of danger with the flying piston projectile, from the shock and vibrations set up by the reaction or recoil like a gun on firing the charge, and the consequent wear and tear.

Notwithstanding the superior economy in gas consumption, these mechanical defects, together with the great bulk and weight of this motor, as well as its noisy, unsteady action, led the inventors to give up the free piston in favour of their well-known compression engine.

### *Gilles Engine.*

In 1874, GILLES constructed an atmospheric engine with free piston, designed to remedy the defects in the Otto and Langen by reducing the *noise* of the rack and clutch, as well as the force of the *recoil* after every explosion. It has two pistons working in opposite directions. The lower working piston A, is connected by rod and crank to the flywheel-shaft; the upper piston B, is free or loose. The slide-valve for admission and ignition is worked off the main shaft by a cam arrangement.

As the working-piston A descends from its highest position, it sucks in the mixture of gas and air between the two pistons; explosion occurs, forcing the working-piston A onwards to the end of its down-stroke, whilst the free piston B is thrown up; its ascent after a time is checked by the cushion of air above it in the cylinder, and in its highest position it is held fast by a clutch. In the meantime a partial vacuum has been formed between the pistons by the cooling of the burnt products, and the piston A is forced up by the atmospheric pressure. Ere A reaches its highest position, B is let go and falls, driving out the burnt products.

This motor was less noisy and more compact than the Otto and Langen, although not so economical, but its weak point lay in the clutch-arrangement, which hindered its success. It was made by Messrs. Simon, of Nottingham, and exhibited in 1878. This firm has since introduced other forms of gas motor.

In the engine patented by HALLEWELL in 1875, the atmospheric pressure is utilised indirectly. The explosion takes place in a vertical cylinder A, closed at the top by a large spring-valve, and containing the free piston, which is thrown up, and in falling forms a vacuum in this cylinder. This vacuum is then put in communication with the exhaust port of the slide-valve on another vertical cylinder containing a double-acting piston, driven by the atmospheric pressure being allowed to act alternately on its opposite sides, like steam in a double-acting steam engine. A lever lifts the free piston to draw in the charge to the cylinder A. The distribution is regulated by revolving slide-valve.

## *Bisschop Engine.*

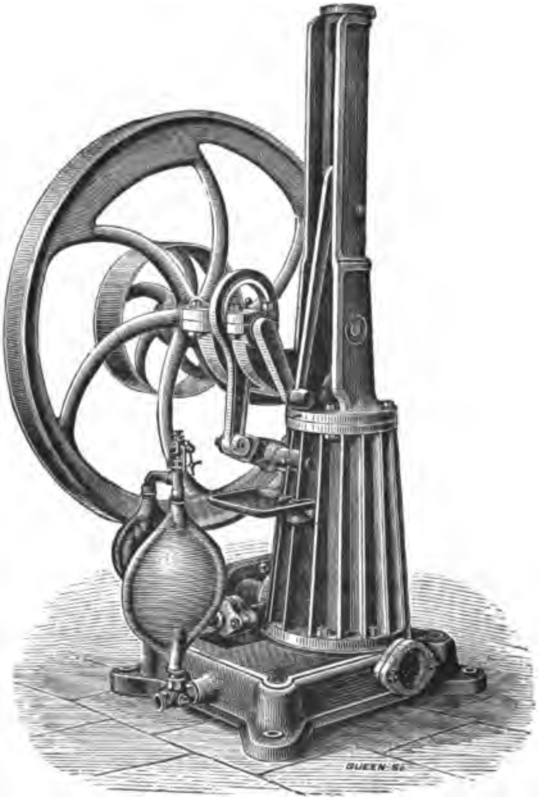
ALEXIS DE BISSCHOP, in 1870, 1872, and 1874, patented and constructed for purposes requiring only very small power, a handy little engine much on the same principle as the Lenoir and Hugon; one idea being to admit the gas and air in stratified layers, and in order to make sure of an explosion the layers rich in gas were ignited first.

Fig. 103 gives a view, and Figs. 104 and 105, sectional elevations of the BISSCHOP engine, as improved by ANDREW.

A long rod connects the crank on the driving-shaft with the crosshead of the piston-rod, which is guided in the open hollow column above the cylinder.

When the explosion takes place, this long connecting-rod and piston-rod are almost parallel, so that the piston then gets a direct pull at the crank without any side pressure on the guide and piston.

FIG. 103.

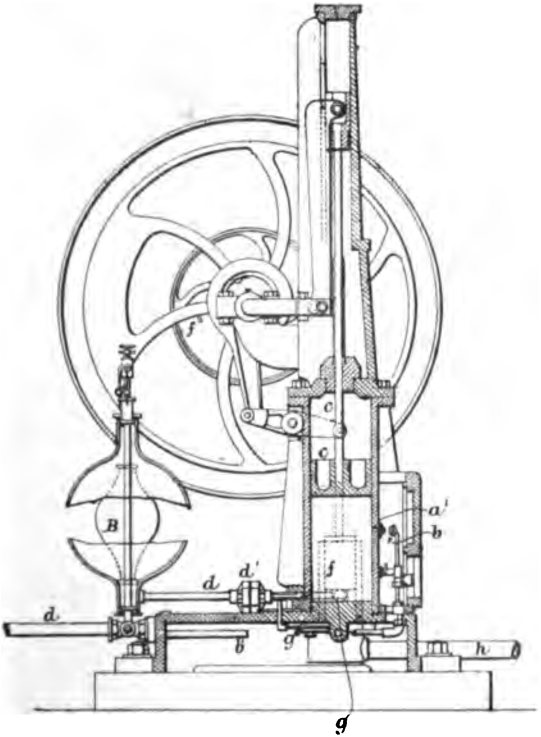


BISSCHOP ENGINE.

A cylindric piston-valve *f*, communicates with the lower part of the cylinder, and is worked by a rocking-lever $f^1$, and eccentric $f^2$, fixed on the driving-shaft. There are two gas jets, one *b* shoots a flame through a hole *a* in the wall of the cylinder, the other is placed beneath to relight *b*.

The engine is fed from two indiarubber bags B, which serve as reservoir and regulator for the gas supply. The gas admission valve *d* consists of a thin iron disk, having holes covered with a circular sheet of indiarubber, which is sucked away from the disk, and allows gas to enter when pressure in cylinder is less than that outside.

FIG. 104.

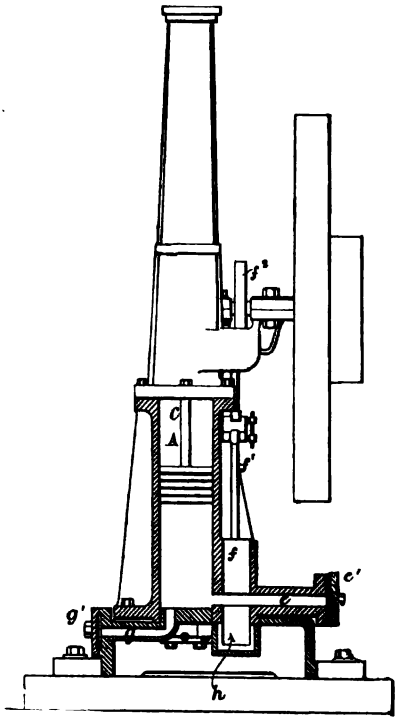


BISSCHOP—SECTIONAL ELEVATION.

Similarly the air-valve *e* is opened by the air pressure outside, and closed by the explosion inside the cylinder. Andrew adds an extra air-valve by which cold air is drawn in at the commencement of the up-stroke to mix with and cool the residual products in the ports. This effects a great saving in gas consumption.

No water-jacket is required, as the engine is kept cool by a number of radial arms or brackets in the casting round the cylinder, which present a large cooling surface to the atmosphere, and give stability to the structure.

FIG. 105.



SECTIONAL ELEVATION (END VIEW).

As the piston is raised, it draws in a mixture of gas and air; at about one-third of its up-stroke, the piston uncovers the lighting-port closed by a steel clack, the flame is sucked into the cylinder and fires the charge, the piston is driven up to the end of its stroke, and the energy thus stored up in the flywheel has to carry the piston through the down-stroke, driving out the burnt products by the exhaust pipe *h*, and one-third of the way up again to draw in a fresh charge.

This engine is adapted only for very small powers, one, two, and four man power (half-horse-power), being the usual sizes. Its great merit lies in the simplicity of its parts, and practically no oil is required except for the bearings. In most other gas engines, oil is a very large item in the working expenses, hence the Bisschop works more economically than indicated by the gas consumption, which is about 120 cubic feet of coal-gas per actual horse-power per hour.

It does not claim to be economical when compared with larger modern engines. It occupies small space, and when once started needs no attention. Hence it is found reliable and suitable for small industries, and is extensively in use.

However, in order to secure greater economy and steadiness of running, Messrs. Andrew & Co., Limited, the English makers of the Bisschop engine, are introducing special forms of their "Stockport" engine in small powers.

The Bisschop motor has been modified and improved by several inventors. Messrs. Rouart Brothers, in Paris, the French makers, have also worked out the practical details carefully.

CARL MAX SOMBART separates the base-plate from the distributor, to avoid the latter heating and to facilitate repairs; he uses a single casting, instead of two weak arms, to carry the shaft; he protects the admission valves against injury from the flame by a perforated sheet-iron disk; and he regulates the admission of gas.

HAIGH AND NUTTALL improve the valves for the admission of gas and air, and use a little bullet to close the ignition hole, instead of the steel clack-valve.

## PETROLEUM ENGINES.

In 1873, J. Hock, of Vienna, took out a patent for a petroleum engine. Air passed through light volatile hydrocarbon as petroleum spirit carries off sufficient vapour at the ordinary temperature to make the mixture inflammable. The air is admitted under pressure, and breaks up the petroleum jet into fine spray and vapour. The mixture is ignited by the flame of combustible gas formed by passing air through naphtha. Hock made the machine work fairly well, but the combustion was incomplete, rendering the efficiency and consumption of fuel unsatisfactory.

This engine was soon superseded by the Brayton Ready-Motor, designed by Brayton, of Philadelphia.

Brayton's patent bears date 1872, but it was not till 1873 that his engine assumed a workable shape, and was tested in New York by Professor Thurston, of the Stevens Institute of Technology. In 1878, the Brayton petroleum engine was introduced into this country by Messrs. Simon, of Nottingham.

A pump is used to compress air and force it through a series of perforated brass disks and materials exposing a large surface of petroleum, in a separate cylinder, so as to thoroughly vaporise the petroleum and insure complete but slow combustion at constant pressure.

In its final form this engine worked well, but required frequent cleaning, as the soot accumulated rapidly.

Careful tests, see page 202, give the consumption of fuel by the Brayton motor at the rate of 0·323 gallons of petroleum (specific gravity 0·850), that is, 0·323 × 8·5 lb., or 2·7 lb. of petroleum per actual horse-power per hour. This is about the same as 50 cubic feet of good coal gas per indicated horse-power per hour.

## MODERN GAS ENGINES.

Thus far our motor has arrived at the first practical stage of its development.

The excitement of 1860 attracted attention, and led many inventors into the field, but the year 1876 marked a fresh era in the history of gas motor engines, for then the invention of the "Otto Silent" was quite a new departure in the application of gas as a motive power. The machine, which had previously been little more than a troublesome and dangerous mechanical curiosity, became a practical and commercial success, in fact, a real rival to the steam engine as a useful and reliable prime mover for small powers.

To Dr. Otto belongs this credit of having made the most successful gas engine to work steadily and with greater economy than was previously known in practice. Thousands of these engines, with improvements in details, have been made and sold by Messrs. Crossley in this country.

Numerous patents have since been taken out for other internal combustion engines. We cannot attempt to give even a brief summary of them.

Many of the designs seem workable and durable, but space will only permit us to deal with the more salient points of those motors which have already established themselves before the public, and which will serve at the same time as representatives of the various types in practice.

# CHAPTER VI.

## CLASSIFICATION OF INTERNAL COMBUSTION ENGINES.

GAS motors may be broadly divided into two great classes, according as the mixture in the cylinder is *compressed* or *not compressed* before ignition.

The class **working without compression** of the charge before ignition comprises *two types of engine:* the *first directly* use the force of the explosion to drive the piston whereas, in the *second or atmospheric engine* this is done *indirectly* by taking advantage of the atmospheric pressure above the piston and of the vacuum produced below it after the explosion.

The **compression engines** may be subdivided into—*first type*, in which the ignition of the compressed mixture is followed up by a more or less *sudden rise of pressure;* whilst in *second type*, the compressed gases burn slowly at *constant pressure.*

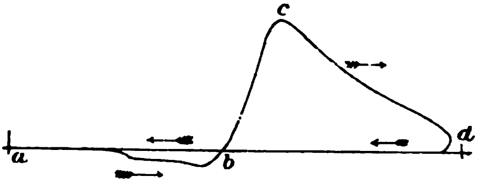
## CYCLES OF THE VARIOUS TYPES.

### CLASS I.—ENGINES WITHOUT COMPRESSION.

*First Type.*—The early **Lenoir** draws into its cylinder an explosive mixture of gas and air, sensibly at atmospheric pressure and ordinary temperature 17° C., for a portion of its stroke. Then, on cutting off communication with the outer atmosphere, the mixture is ignited, the temperature rises to about 1600° C., the pressure quickly increases, followed by expansion of the burning gases driving the piston forward, and doing work during the remainder of its stroke. In the return stroke, the piston drives out the products of combustion.

Fig. 106 shows the actual diagram of the Lenoir motor.

FIG. 106.



INDICATOR DIAGRAM FROM EARLY LENOIR.

The cycle of this type of motor is characterised by the three following periods :—

1. *a*, *b*. Drawing in explosive mixture of gas and air, sensibly at atmospheric pressure.

2. *b*, *c*, *d*. Explosion and expansion of the mixture driving the piston forward during the working stroke.

3. *d*, *a*. Driving out burnt products to exhaust, during return stroke of the piston.

The consumption of coal gas in motors of this type may be taken as follows :—

| | | |
|---|---|---|
| Lenoir | 95 | cubic feet per indicated H.P. per hour. |
| Hugon | 74 | „ „ „ „ „ „ |
| Bisschop | 80 | „ „ „ „ „ „ |

## CLASS I.

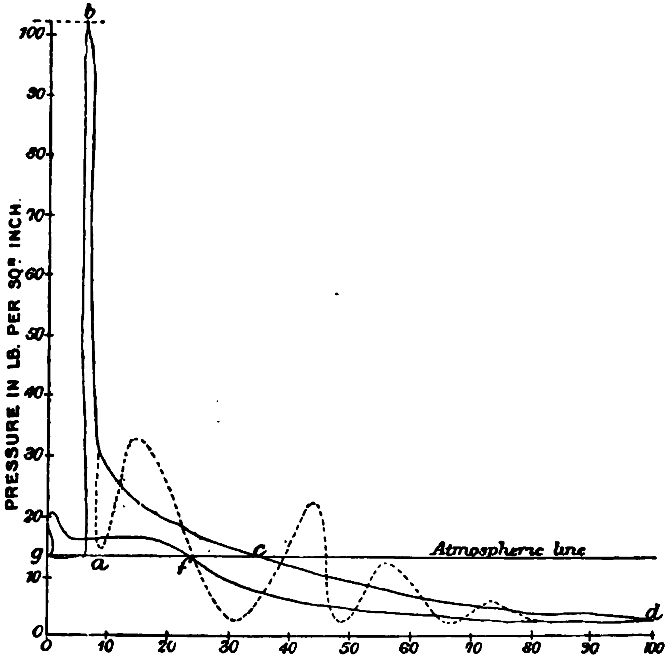
*Second Type.*—**Atmospheric engines,** as the **Otto and Langen.**

The explosive mixture of gas and air is admitted at atmospheric pressure for a portion of the stroke. Then explosion follows with sudden increase of pressure, which drives up the free piston, out of gear, with great velocity. There is a great range of expansion, which, together with the cooling of water-jacket, reduces the pressure below atmospheric, and when all the energy of the explosion is spent, the piston is brought to rest by its own weight and the external air pressure.

Then the piston coming down slowly by its own weight, by the partial vacuum, and mainly by the atmospheric pressure, is put in gear with the driving-shaft, and does useful work, and finally expels the burnt products.

This action is characterised by the sudden explosion and recoil, just as in a gun, the piston being the projectile. The rapid rise in pressure causes great vibrations in the indicator spring, and, consequently, vagueness in the diagram. The great and rapid expansion is important, since the energy of explosion is rapidly stored up as potential energy, to be given out more slowly whilst the piston steadily descends under atmospheric pressure.

FIG. 107.



OTTO AND LANGEN ENGINE (FREE PISTON).

The actual diagram, Fig. 107, shows the cycle of this type of motor.

1. *g, a.* Admission of explosive mixture.

2. *a, b.* Explosion at almost constant volume, followed by great expansion *b, c, d,* until the pressure falls below atmospheric during up-stroke of free piston.

3. Down-stroke of piston doing work along *d f,* and driving out the cold products of combustion from *f* to *g.* This engine consumed only 21 cubic feet of gas per horse-power per hour; but could only be used for small powers, owing to structural defects.

Amongst *atmospheric* engines of this type are those of Barsanti and Matteucci, Gilles, Hallewell, Robson, and others.

## MECHANISM FOR IGNITION, ADMISSION, AND GOVERNING.

### *Ignition.*

In this first class of early engines without compression, the IGNITION of the charge was a comparatively easy task. This was generally done by sucking or shooting into the explosive mixture of gas and air a flame kept burning outside the cylinder, relighted, if necessary, by another gas burner. At a given point of the admission stroke, generally about a third in the first type, the motor piston uncovers a touch-hole closed by a small clack or lid, which the pressure of the atmosphere opens and pushes towards the cylinder, at the same time admitting the flame which is sucked into the cylinder from the burner. Such is the mode of ignition in the Bisschop, Hutchinson, and Robson motors.

In other engines the ignition flame has been strengthened by an *exploder,* that is, the mixture is not directly lighted in the cylinder, but a small portion of the charge is ignited in an adjoining chamber connected to the cylinder. The ignition flame is sometimes fed separately from a rubber bag, as in the Bisschop and Hugon.

The ignition is best effected by the *slide-valve* itself, which contains a small *lighting chamber,* and carries with it a flame from the gas burner outside, whilst it shuts the lighting port when explosion commences.

*Platinum wire heated to incandescence* is rarely employed in motors of the first type; one instance is in the machine of the Economic Motor Company, in which a platinum disk is kept red hot by a blow-pipe flame.

Although *Electricity* was the first means adopted for lighting, we find the ELECTRIC SPARK *given up for a time* or but rarely used in later engines, because it was found uncertain and gave trouble in the Lenoir.

The mechanical details of devices for ignition are dealt with in Chapter VII., page 217.

### *Admission.*

**Admission** of the gas and air is usually effected by a slide very like the slide-valve of a steam engine, the only essential difference being the additional ports necessary for lighting. Thus we find, for the admission of gas and air, counterbalanced cylindric slide-valves employed in the form of oscillating cocks, as in *Haigh* and *Nuttall's* machines, revolving in those of *Linford* and *Tonkin*, or as slides in the *Bisschop*, *Hugon*, and *Lenoir*. In the *Hallewell* a disk is used. The plate-slide is found in many engines, and may be more easily repaired than the cylindric piston-valve.

The gas and air are sometimes mixed and stratified by passing in separate currents through little holes bored in the plate.

Some inventors, notably *Andrew*, think it necessary to admit to the working cylinder a certain quantity of the mixture directly, by simple suction, independently of the admission made by the slide, in order to ease the slide, and to be able to reduce its dimensions.

Most frequently the burnt products are expelled by the return stroke of the piston; in some motors, as the *Schweizer* (1883), part of the products is left in the cylinder beyond the piston, as a cushion or buffer, to deaden the shock of the explosion. In other engines, on the contrary, the burnt products are completely swept out of the cylinder after each explosion by means of a pump (*Turner*), by an auxiliary piston (*Robson*), or by a ventilator (*Schweizer*).

Many attempts have been made to *reduce the shock of the explosion*, which is so sudden in this class of motor; the use of a cushion of air, or, at least, of a poorer mixture, before the charge proper, seem intended for this purpose, but the increased volume of the cylinder and complication in the mechanism make the end difficult to be attained, as in *Withers*, 1882.

*Bisschop* seems to have the best and simplest arrangements. Heating is so slight in small engines of this type, in comparison to that of the compression engines of high powers, that it is rarely necessary to use the circulation of water to cool the cylinder. It suffices in the *Bisschop* to use radial arms presenting a large cooling surface.

### *Governing.*

The **governing mechanism** is almost similar to that in steam engines—the *centrifugal governor reduces or stops the admission of gas.* Indiarubber bags or reservoirs are interposed between the engine and gas main to keep the pressure of the gas supply steady.

If great regularity or steadiness of motion is desired, these motors may be coupled together to make a machine of several cylinders, as in the *Linford.* Fly-wheels may also be made large and heavy, within certain limits determined by practice, and the different moving parts must in every case be carefully balanced.

## CLASS II.—COMPRESSION ENGINES.

### FIRST TYPE.

This important class of gas motors are by far the most largely used, and have proved practically successful, showing the advantages of **compression.**

The cycle in this type of engine comprises four operations:—

1. *Charging or drawing in* a mixture of gas and air at atmospheric pressure.

2. *Compression* of the charge in the cylinder to a pressure of from 40 to 60 lb. per square inch.

3. *Combustion and Expansion.* The temperature rises to about 1600° C., and the expansive force of the burning gases drives forward the piston, performing work.

4. *Discharge* of the products of combustion by exhaust at atmospheric pressure.

There are two varieties of this type represented by the OTTO and CLERK engines respectively—in the *Otto* all the operations take place in the motor cylinder, containing one piston, and there is an explosion or working stroke every two revolutions; whereas the Clerk engine has an auxiliary cylinder, with pumping piston or displacer for drawing in, mixing, and sending the charge into the working cylinder, where it first sweeps out the products of the previous combustion, and is then further compressed by the motor piston; an explosion taking place every revolution.

## Otto Gas Engine.

The objectionable features in the design and noisy action of the free piston engine of Otto and Langen induced these inventors to return to the principle of direct action, and to abandon the idea of utilising the vacuum produced after the explosion when the expanding gases are cooled. They get rid of the inconvenient recoil and vibrations due to the high initial pressures suddenly arising from the explosion of strong charges, by varying the richness of the mixture; so that the rate of combustion is made more nearly comparable with the piston velocity.

It was observed that the rapidity of burning, or the rate at which the pressure was developed by the combustion of an explosive gaseous mixture in a closed vessel, was lessened by the presence of those inert gases, such as nitrogen, which do not enter into combination with any other gas present.

Experiment showed that by varying the strength of the mixture, the *rate of combustion could be varied*, and was thus completely under control. With a weak mixture the combustion took place slowly, whilst the inert diluting gases absorbed a large quantity of the heat generated.

In the patent No. 2081 of 1876, Dr. Otto proposed to arrange an imaginary stratified mixture, composed first of a portion of the burnt products from the previous explosion left in the cylinder next the piston. This layer was intended to dilute the incoming charge, and act as a cushion to deaden the shock of the explosion. He introduced pure air during the early part of the admission stroke, and then the combustible mixture of air and gas was admitted, becoming richer in gas until the air port was closed and gas alone entered the cylinder at the end of this stroke.

This *stratification* idea is now generally admitted to be *erroneous;* and it is, moreover, inconsistent with the nature of gases to remain in distinct layers or slices when agitated as in the engine cylinder. Experiments with smoke in glass models, the *same size* as the Otto cylinder, show that the great velocity of the gases rushing into the cylinder projects them against the piston, producing eddies or whirls, whilst the whole contents of the cylinder are mixed by the commotion and crowding together of the gaseous particles on the return of the piston during the compression stroke.

However, the richer mixture near the touch hole made the charge more easily ignited, whilst the dilution of the charge, by the residual products, undoubtedly led to the gradual and prolonged combustion, the German *nachbrennen* or afterburning, throughout the explosion stroke.

Now in the engine cylinder, the temperature of the gaseous mixture is raised by compression before ignition whilst exposing a smaller surface for cooling per unit mass of gas. At the same time, compression makes the poor mixture more readily inflammable, and increases the rate of propagation of the flame throughout the entire mass. Moreover, the change of pressure by the explosion will not be so sudden as to cause serious wear and tear in the mechanism which is prepared to receive the shock.

The "Otto Silent" engine was designed to embody all these points, using the cycle proposed by Beau de Rochas with high velocity of piston, comparatively small cylinder and initial compression followed by slow but prolonged and, if possible, complete combustion, retaining some of the burnt products in the cylinder to commingle with and dilute the incoming charge.

This engine has been considered above in Chapter II.

The economy and great gain of efficiency in this engine is mainly due to compression of the charge before ignition.

## Modern Lenoir Engine.

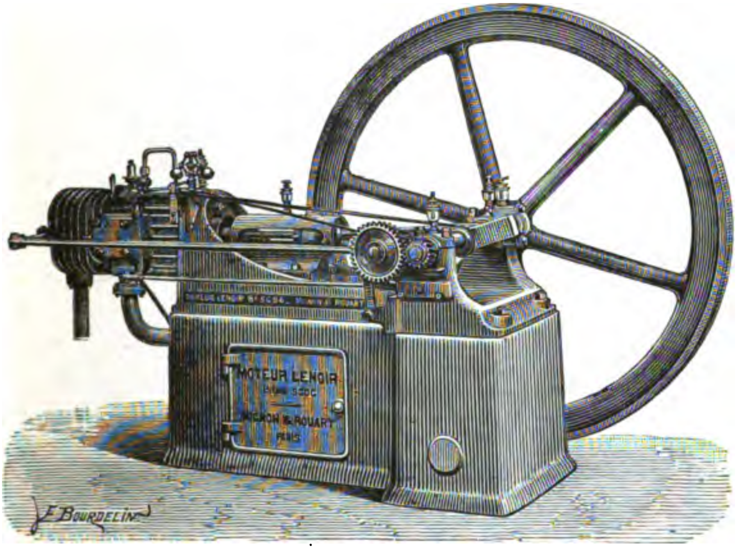
In 1883, LENOIR brought out a new compression engine of this type, Fig. 108, with exactly the same cycle as the Otto.

All the operations are performed in one cylinder. The front end of this cylinder is made into a special compression chamber, like a *cartridge*, called the "*reheater*," provided with deep, strong ribs in the casting, exposing a large cooling surface to the air; whilst the water-jacket is only around that part of the cylinder swept by the piston.

The *slide valve is altogether done away with*, and simple disk or mushroom valves used instead, for admission and exhaust, worked by levers from cams on the side shaft. The exhaust valve is placed at the base of the *cartridge* or *reheater*, and allows the rejection of all the burnt gases.

The charge is ignited by the electric spark from a Ruhmkorff induction coil, between two points immediately above the admission port. The charge of gas and air is sucked into the cylinder by the piston, and compressed to at least 4 atmospheres pressure in the cartridge at a high temperature which facilitates ignition, permits the use of poor mixtures, and gives complete combustion. Since the mixture is compressed to 4 atmospheres before ignition, the maximum explosion pressure reaches 12 or 13 atmospheres, and this is followed by a long range of expansion.

FIG. 108.



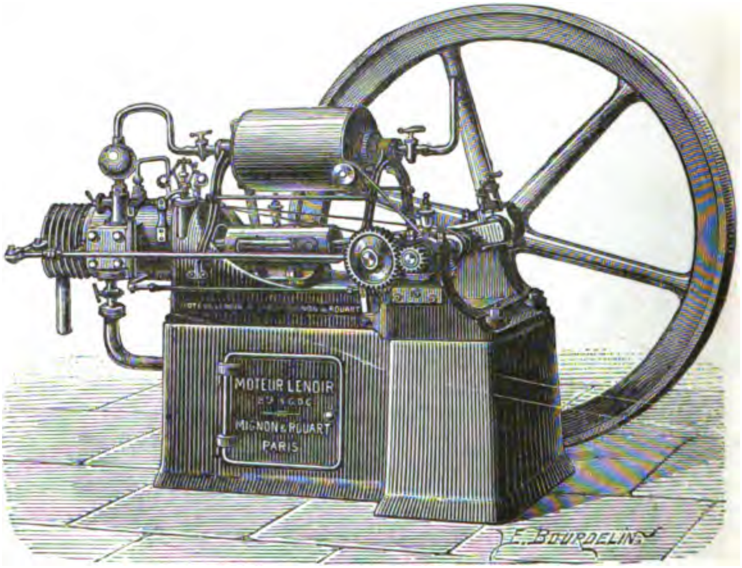
THE NEW LENOIR ENGINE, 1883.

A simple *centrifugal ball governor* regulates the speed by raising a lever so that it misses the admission-valve spindle, and thus cuts off supply when the speed is too high.

Messrs. ROUART FRÈRES, of Paris, also make this new Lenoir engine to work with petroleum spirit or gasoline.

The novel feature in this petroleum engine, Fig. 109, is the *carburator.* For some time Lenoir rotated a cylinder provided with sponges dipping into petroleum every revolution, and brought in contact with air. He abandoned this carburator in favour of that shown in Fig. 109, which consists of a metal cylinder with little metallic vanes or troughs soldered to a drum inside it. The cylinder is nearly filled with petroleum spirit, and made to rotate so that the liquid hydrocarbon is lifted by the troughs as they turn round, and dashed out in fine spray, which is partly evaporated, whilst the air drawn through the cylinder, from one end to the other, is charged with the inflammable hydrocarbon vapour. This carburetted air, passing through a U-shaped tube and rubber bag, is mixed with ordinary air and admitted to the *cartridge* or *reheater* in the motor cylinder, where the mixture is heated and compressed to prepare it for ignition by the electric spark.

Fig. 109.



Lenoir Petroleum Engine.

Mounted on wheels, like the Priestman oil engine, the Lenoir becomes a portable agricultural motor driven by petroleum spirit. It is furnished with a water-tank to supply the cylinder jacket, and the circulation is kept up by a little centrifugal pump driven by the motor.

M. Alfred Tresca has made several trials of the Lenoir petroleum motor, using as fuel gasoline of density 0·650, that is, weighing 650 grammes per litre. On the 26th December, 1885, a 4 horse-power portable agricultural motor, during a trial run of 4·5 hours, consumed gasoline at the rate of 0·629 litre per *cheval-heure*. Taking the price of gasoline as 50 centimes a litre, one *cheval-heure* costs 32 centimes, that is, about 3·2*d.* per horse-power per hour.

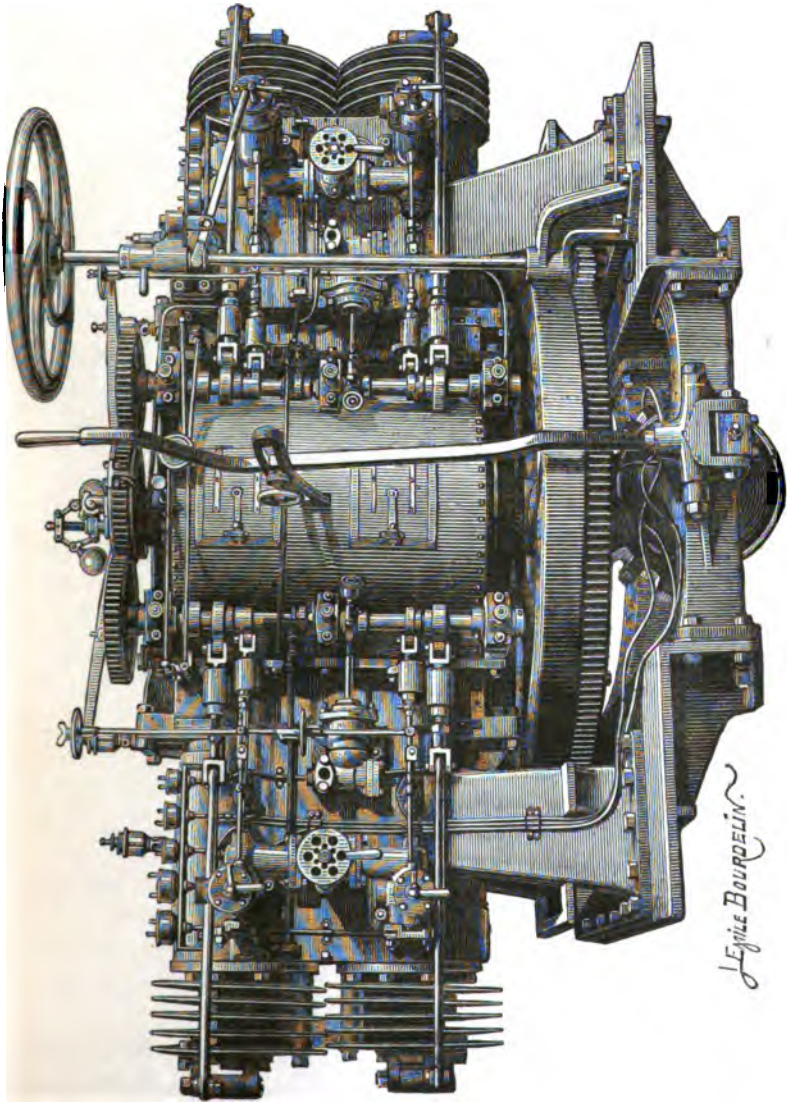


FIG. 110.

LENOIR PETROLEUM ENGINE (20 H.P.) FOR BOAT.

The screw propeller of a boat may be driven by the **petroleum engine,** Fig. 110. It consists of two twin cylinders, with the crank shaft vertical, and carrying on its lower end a horizontal fly-wheel, which also adds to the

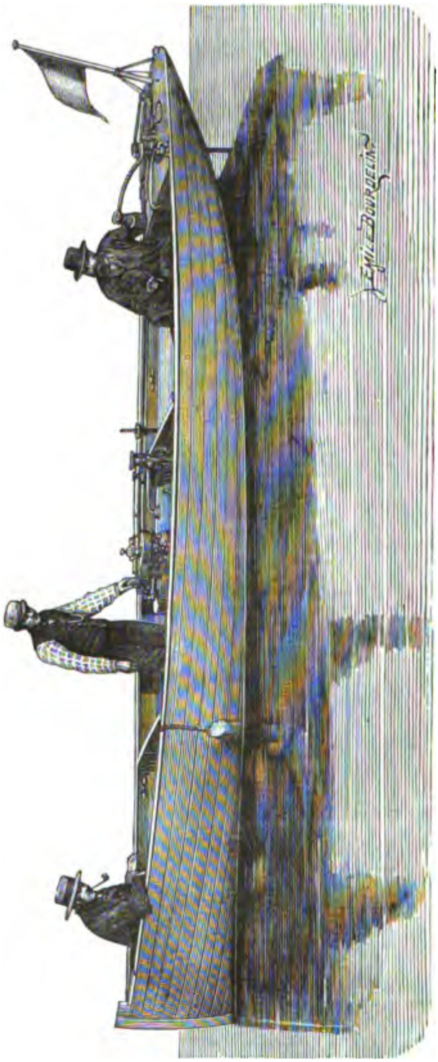


FIG. 111.

LENOIR PETROLEUM LAUNCH.

stability of the boat. The motive power may be varied by using only one or two cylinders at a time. The propeller shaft is horizontal, and driven by bevel and cog-wheel mechanism. It can readily be thrown into gear, reversed, or stopped by means of the lever behind the engine.

The arrangement of the engine on board the launch is seen by Fig. 111.

This is not so handy or convenient as the Zephyr launch, in which the petroleum tank and engine are stowed away in the extreme bow and stern, leaving plenty of room in the middle of the boat for passengers.

The fuel consumption for an engine of 3 horse-power effective is about 400 grammes of gasoline per hour per horse-power.

## Clerk Engine.

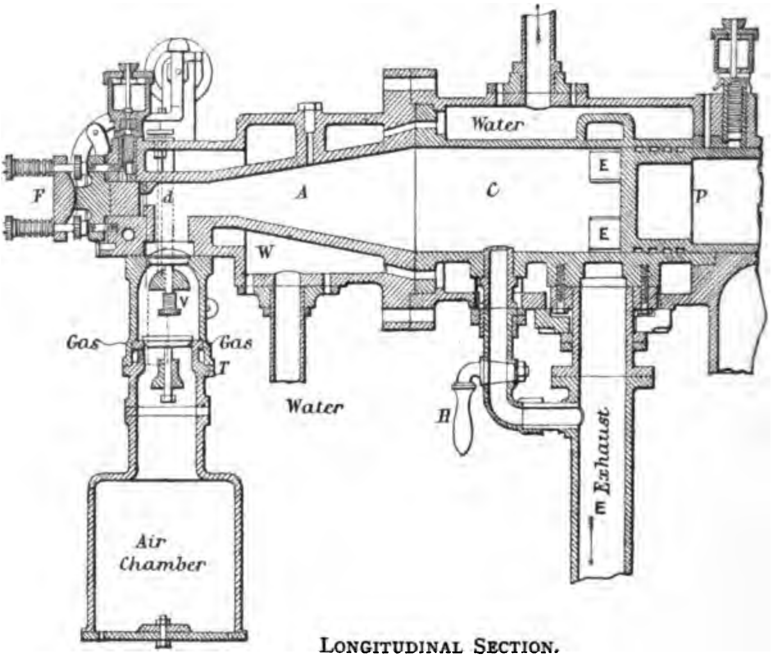
Figs. 112 and 113 show the sectional elevation and plan of the gas engine invented by Mr. Dugald Clerk, and made by Messrs. Thomson, Sterne, & Co. The Clerk engine, which reached this stage of its development in 1880 (drawings from Patent No. 1089 of 1881), was designed to give an impulse or explosion every revolution, performing in the same time a complete cycle of operations. To do so, Clerk used an auxiliary cylinder, with displacer and piston for sucking in the measured charge of air and gas, and delivering it into the motor cylinder, where it was compressed by the motor piston before combustion.

C represents the working cylinder, open at one end, and having a deep piston P, joined to the crank (not shown) by a connecting-rod as in ordinary engines. This cylinder, surrounded by water-jacket W, has a conical clearance chamber A, into which the charge of gas and air is compressed before being fired.

The exhaust ports E E open into an annular space round the cylinder, leading to the exhaust pipe E, by which the burnt gases escape when the piston uncovers these ports.

The capacity of the displacer cylinder B is about double the product of the area and stroke of the working piston. The displacer piston D is worked from the fly-wheel, and its crank is set a little over 90° in advance of the motor crank on the main shaft.

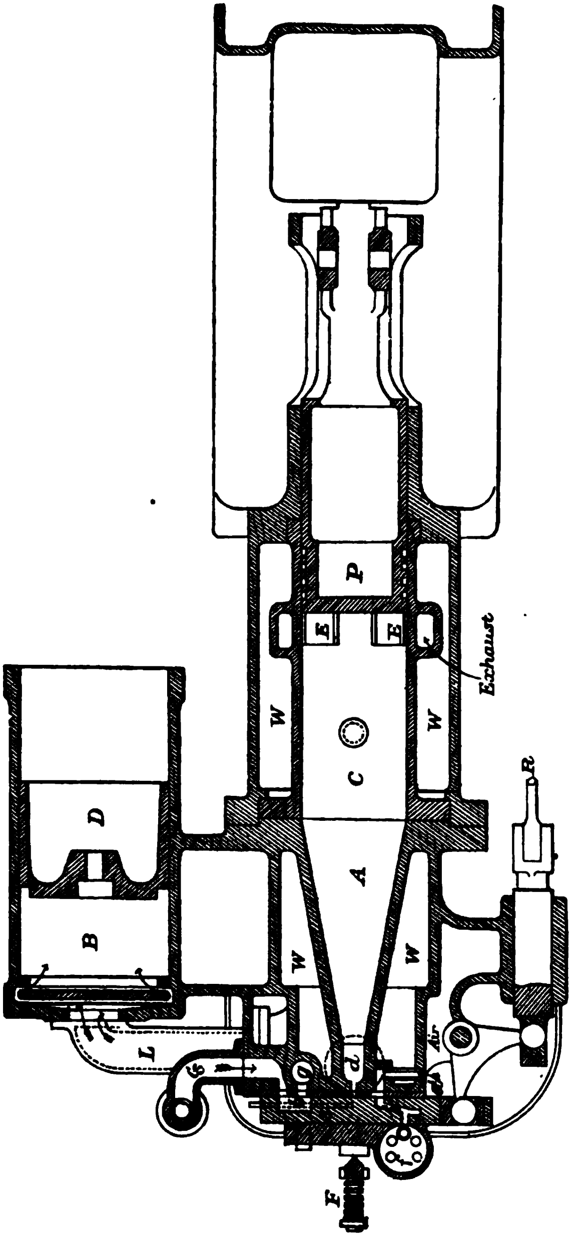
FIG. 112.



LONGITUDINAL SECTION.

During its forward stroke, D draws the explosive mixture of gas and air into the cylinder B. First, the gas is drawn by the pipe S, Fig. 113, the slide port *b*, the conduit *g*, the valve T, and the pipe L into B, through an annular orifice round the baffle-plate made to check the eddies or inrush of the gas. The conical seated valve T has holes round it to admit a proper mixture of gas and air—the latter being drawn through the indiarubber flap-valve at the bottom of air chamber.

FIG. 113.



SECTIONAL PLAN.

About the middle of the forward stroke of the displacer piston D, the slide-valve *s* closes the orifice *g*, and thus cuts off the supply of gas by the slide-port *b*, so that pure air alone is admitted into the passages by the valve T during the second half of the stroke. The forward stroke of D is completed while the working piston P is moving forward rapidly near the middle of its working stroke. In the return stroke, D now begins to compress the charge a little, but this does not open the valve V, as the pressure on the other side is much greater.

Near the end of the forward stroke of P the exhaust ports E are uncovered, the burnt products begin to flow out through E, whilst the displacer piston D discharges the air out of B back through the pipe L, the valve V lifted by the suction of the exhaust, and the passage *d*, into the compression chamber A of the working cylinder. This air displaces or sweeps before it the products of combustion out into the exhaust E. During the second part of its return stroke, the displacer piston D also forces the explosive mixture out of B after the air into A, when the piston P is at the first part of its return stroke. This action continues until just before P covers the exhaust ports. Almost the whole of the burnt products have been expelled, and a portion of the newly introduced charge is also following; but since this first portion is nearly pure air, it may be allowed to pass out after the products of combustion by the exhaust, without losing any appreciable quantity of the mixture rich in gas behind it.

However, owing to the difficulty of exactly proportioning the volumes of the displacer and motor cylinders, as well as to the tendency of gases to mix, some of the unburned gas usually does escape with air into the exhaust. At the same time some of the residual products may be retained to prevent loss of the unburned gas mixed with it.

The exhaust is now closed by piston P in its return stroke; the piston D begins its next forward stroke, and the valve V is closed by its spring.

Both of these automatic lift-valves are provided with quieting pistons, which compress air and act as guides and dashpots to check the sudden fall of the valves on their seats.

The explosive mixture in C and A is compressed by P until it occupies only the conical clearance chamber A of the cylinder, then the charge is fired. This is done by a flame carried under pressure in the slide *s*, moved to and fro by the bell-crank lever acted on by connecting-rod R joined to an eccentric on the crank shaft. A chamber *b'*, in the slide-valve S, communicates with the bottom of the combustion chamber A, and receives a regulated quantity of the explosive mixture through a grating or "diffusor" when in the position Fig. 112. This mixture in *b'* is lighted at the constant burner *f*, getting air from atmosphere through the little passage *a*, Fig. 113. After the chamber *b'*, carrying the flame, is isolated by the movement of the slide, it receives more of the compressed mixture through the "diffusor," this augments the burning and pressure until *b'* is brought opposite *d* and shoots a tongue of flame into the compressed charge.

The slide-cover is pressed against the slide-valve by the spiral springs F.

In starting the engine, turn the cock H, Fig. 112, which opens the back of the motor-cylinder to the exhaust, so as to diminish the compression.

There is an explosion every revolution at full load, and the operations in this engine are as follows:—

For the *displacer cylinder;* during the forward stroke of piston it sucks in—

1. An explosive mixture of gas and air necessary for the next charge in the working cylinder;
2. Towards end of stroke only air, which is supposed not to mix or diffuse into the explosive mixture.

During the return stroke the displacer piston drives into the motor cylinder, aided by the suction of the exhaust—

1. The scavenger charge of air;
2. The explosive mixture.

By the indicator diagram, Fig. 114, taken at the same time from the *motor cylinder*, it is easy to follow the cycle. The full lines give the real diagram; and the dotted lines show the

FIG. 114.

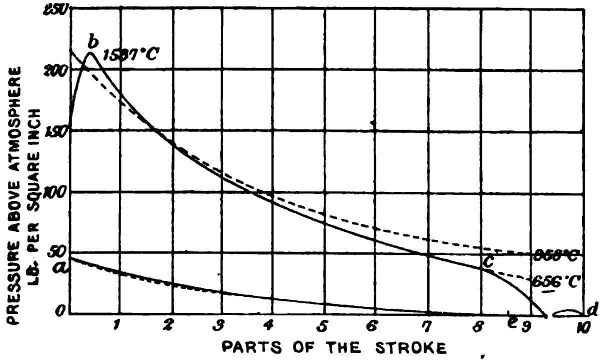


DIAGRAM FROM CLERK GAS ENGINE.

compression and expansion of air without loss or gain of heat under similar conditions of temperature and compression.

From *a* to *b*, explosion of the mixture at nearly constant volume.

*b* to *c*, expansion of the burning gases, first above and then below the adiabatic curve.

*c* to *d*, exhaust begins, and the products of combustion are driven out before the air and incoming charge from the displacer cylinder.

*d* to *e*, end of exhaust and charging.

*e* to *a*, compression of the mixture to one-third its original volume, nearly along the adiabatic.

With this diagram Mr. Clerk gives the following particulars:—*

Diameter of cylinder, 6 inches; length of stroke, 12 inches; speed of engine, 150 revolutions per minute; mean available pressure, 70·1 lb. per square inch; giving 9 indicated horse-power. The maximum pressure is 220 lb. per square inch above atmosphere. The pressure before ignition is 41 lb. per square inch above atmosphere. The lower dotted line shows compression without loss of heat to the same volume as exists in clearance space. Temperature before compression, 17·3° C. (60° F.) Temperature after compression 150·5° C. The upper dotted line shows the work done by air heated to 1537° C., supposing it to lose no heat during expansion, except by doing work. The actual diagram shows a mean pressure during $\frac{8}{10}$ of stroke of 78 lb. on the square inch, which is equal to 6851 foot-pounds per cubic foot of combustible mixture used. The dotted lines show an available pressure of 89·8 lb. per square inch, which is equal to 7888 foot-pounds per cubic foot of air compressed. Duty $= \frac{7{,}888}{24{,}416} = 0{\cdot}323$.

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* See *Minutes of Proceedings Inst. C.E.*, vol. lxix. part 3, session 1881–82.

Consumption of gas 22 cubic feet per indicated H.P. per hour; that is to say, 17·83 per cent. of the heat of combustion is turned into work.

It will be observed that here the expansion is only continued until the volume of the burning gases becomes equal to the volume occupied by the charge before compression. Moreover, compression takes place in the motor cylinder. In ordinary working, the gas consumption is usually found to be greater than these figures indicate. For a time this engine was fairly in competition with the Otto, and the impulse every revolution gave it the decided advantage of greater regularity of running; but this was counterbalanced by the additional cylinder and displacer piston required. Unfortunately this form of the Clerk engine is not now prominent in the market, but the inventor has been working out another form of gas motor.

## Stockport Engine.

In another modification of this type of compression engine, giving an explosion or impulse every revolution, the charge is mixed and partly compressed in a separate cylinder or chamber which feeds the motor cylinder.

Messrs. J. E. H. Andrew and Co., Limited, make such an engine (Andrew's patent), called the STOCKPORT: the name of the town where it is constructed. The original type is greatly modified, and although several thousands of these

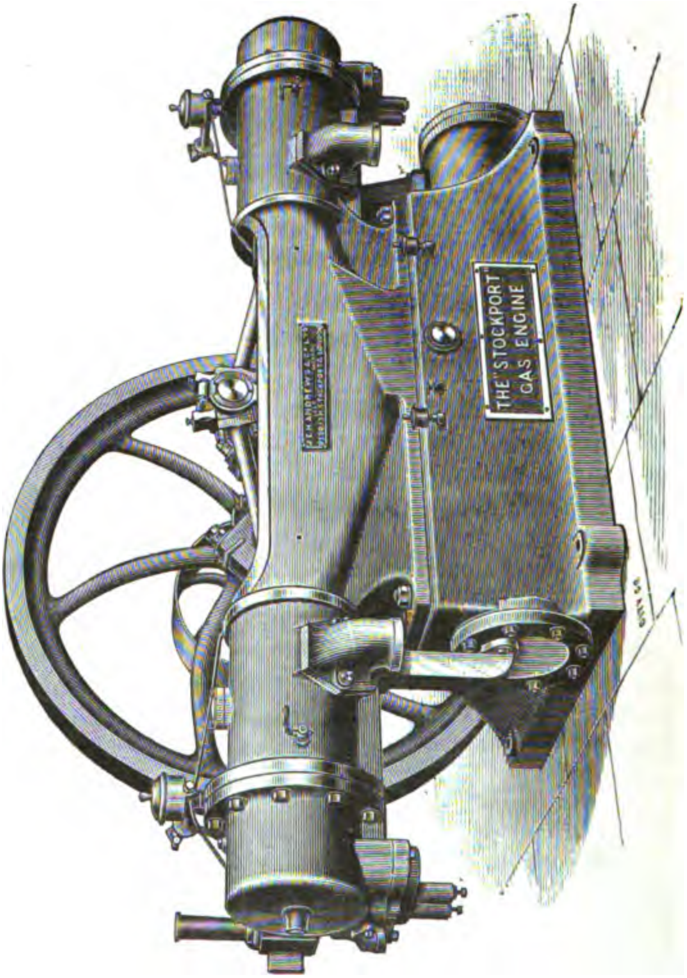


FIG. 115.

STOCKPORT DOUBLE-ACTING ENGINE.

engines have already been made and sold in Great Britain, the details of the design are still being modified and improved as experience is gained.

In the early forms the displacer cylinder is fixed opposite the motor cylinder on the same axis, so that the piston is a double trunk with the crank shaft between the cylinders.

The two cylinders communicate with each other by a chamber in the base of casting. The charge of gas and air is drawn in through a slide valve, the admission being controlled by a governor. The pump cylinder draws in the mixture, compresses it and supplies the motor cylinder every revolution. Towards the end of the explosion stroke the motor piston uncovers the exhaust port, and the residual products are rejected before the incoming charge, which is still further compressed by the motor piston before being fired.

Here obviously one of two things, if not both, must occur: either part of the charge of gas and air escapes with the burnt products by the exhaust, or else a considerable portion of these products is retained in the cylinder with the fresh charge. Hence, unless the engine is very carefully made to the proper proportions, there is likely to be waste of gas to the exhaust, and consequently the gas consumption will be high.

The *mode of ignition* is by heated tube (see page 232), but the ordinary slide-valve, with flame from a constant burner outside, is sometimes used in large engines, where considered more suitable for the work required to be done.

The *indicator card* taken from the motor cylinder is like that from the Clerk engine, Fig. 114, with a good range of expansion. However, the action in the two engines differs mainly in the use of the scavenger charge of air by Clerk, which is probably sacrificed in the Stockport at the expense of some gas.

The *double-acting type* has two motor cylinders opposite each other, with their piston rods attached to a common crank on the main shaft as shown in Fig. 115. The same is true of the pump cylinders placed *below and parallel to* the motor cylinders which they supply. By this means, two impulses are given to the driving shaft every revolution, except when the governor acts, and with a suitable fly-wheel great steadiness in running is obtained.

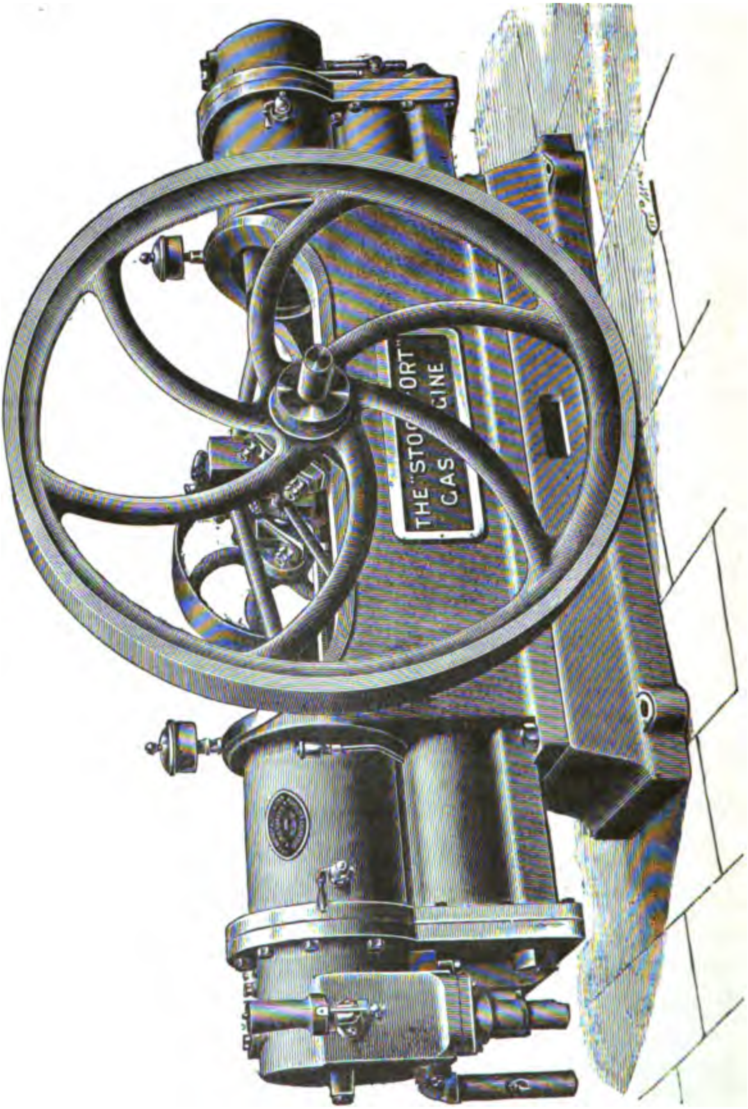


Fig. 116.

Improved Double-acting Engine.

An improved form of this double-acting type is shown in Fig. 116. This really consists of two independent engines, with their motor cylinders placed in a line opposite one another, and the charging cylinders arranged in the same way, each underneath the cylinder it supplies. With full load this device secures two impulses every revolution of the crank shaft, and, consequently great regularity in running. The mechanism is so arranged that the pair of cylinders at either end may be thrown out of action, and the other pair run alone when the load is light.

A couple of these double-acting engines may be formed into one compound **quadruple-acting engine,** having four pairs of motor and charging cylinders, with fly-wheel placed in the centre between them. In this way, almost any power can be obtained with uniform driving effect.

These gas engines are therefore well adapted to drive machinery requiring constant speed, as dynamos for electric lighting purposes.

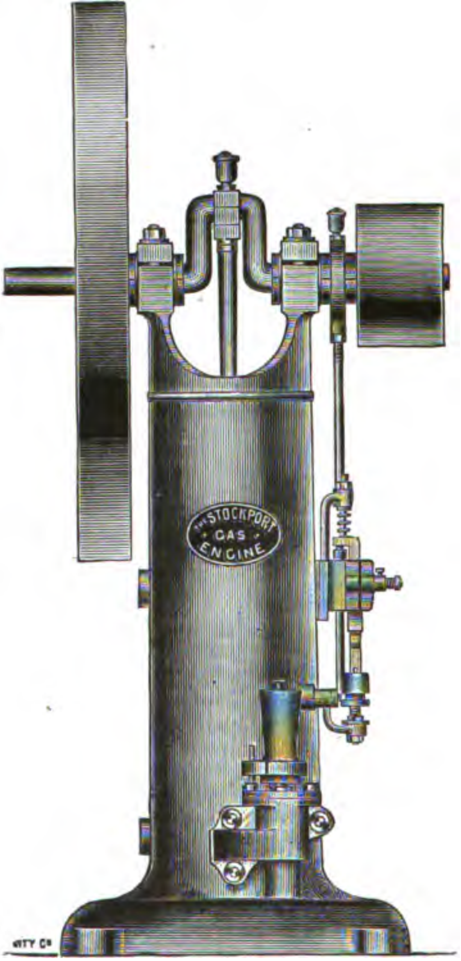
## Single-acting Vertical Stockport Engine.

A *small vertical Stockport engine,* Fig. 117, is also made, which occupies very little space, and is suitable for many purposes requiring small power, up to $\frac{3}{4}$ horse-power.

In this design, the one piston is different in diameter at its two ends, and serves not only to draw in and compress the charge, but also to receive the working impulse. The upper part of the piston, travelling to and fro in the charging cylinder, is larger in diameter than the lower part which fits the small motor cylinder at the bottom of the column.

The mixture of gas and air is drawn into the cylinder by the charging end of the piston, and thence forced down by it through the non-return valve into an annular space around the top of the motor cylinder, into the lower part of which it is compressed in the usual way before ignition. The charge is fired by a heated tube. There is no slide-valve in the engine. The combustion cylinder is surrounded by a water-jacket.

FIG. 117.



SMALL SINGLE-ACTING STOCKPORT.

The engine is regulated by a sensitive governor, which opens or closes the charging valve to keep up the normal speed. This governor consists of a mass vibrating about a vertical spindle, and is fitted with a spring that can be tightened by a thumb-screw to suit the particular speed desired.

## Simon Engine.

Mr. Richard Simon, of Nottingham, has also built a gas engine, in which the cylinder is divided into two parts of different diameter, fitted with a differential piston.

The arrangements about the cylinder are seen in vertical section, Figs. 118 and 119, and in horizontal section Fig. 120.

Fig. 118.

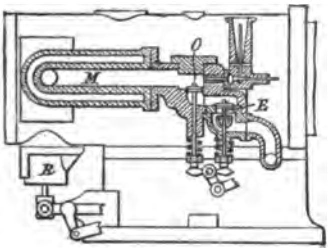
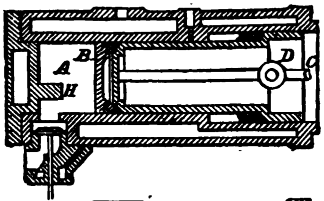


Fig. 119.



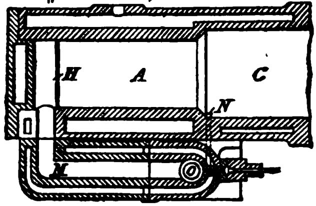


Fig. 120.

Cylinder of Simon's Engine (1889).

The piston has two parts or heads, the smaller part B, Fig. 119, works in the motor or explosion cylinder A, whilst the larger one D works in the charging end C. These two ends of the cylinder are connected by the pipe M.

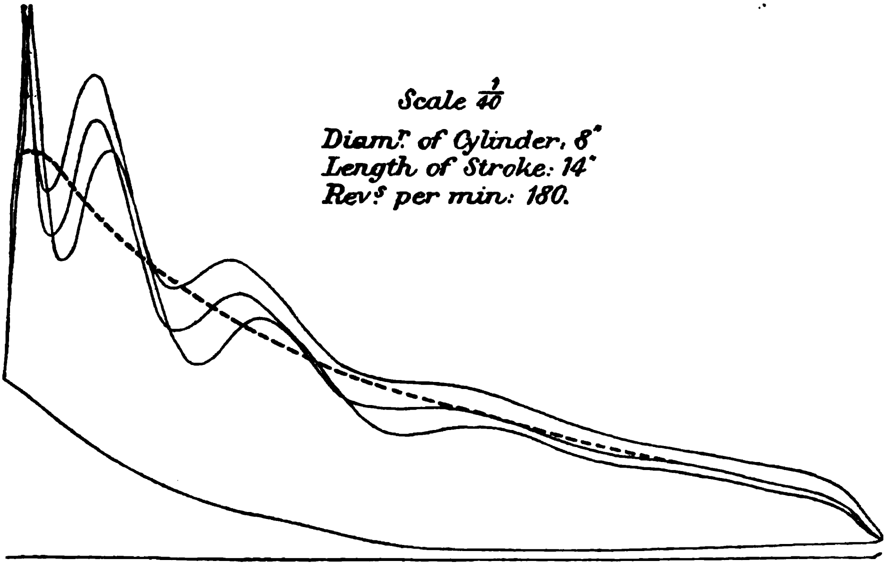
The cylinder is water-jacketed at every available point.

The valves are held down against their seatings by spiral springs, and opened by levers joined to one common link, which is worked by a cam on the crank shaft. These levers are so contrived that the exhaust valve R is opened a certain interval of time before the valve O allows the fresh mixture of gas and air from the charging cylinder C into the pipe M, and explosion cylinder A.

During the *out-stroke* of the piston from end A, the working piston B is driven by the burning and expanding charge, and at the same time the new mixture of gas and air is being drawn into C, by the head D, through the port N and double-valve E, Figs. 118 and 120.

Sufficient energy is now stored up in the fly-wheel to carry the engine through the return-stroke. During the first part of stroke, the exhaust valve is opened, and some of the burnt products are ejected by the piston B before the incoming charge that is being forced from cylinder C by the part D of the piston.

FIG. 121.



INDICATOR CARD FROM SIMON ENGINE.

The division wall or shelf H, Figs. 119 and 120, is designed to divert the inrushing current of gas and air from the exhaust R, and thus avoid loss of the rich mixture along with the burnt products. At about half-stroke the exhaust-valve is closed, and the charge is compressed into A and the passage M, during the remainder of the stroke.

When the piston has commenced its next out-stroke, the highly compressed charge is fired by the heated tube, Fig. 118, ignition first taking place in the passage M.

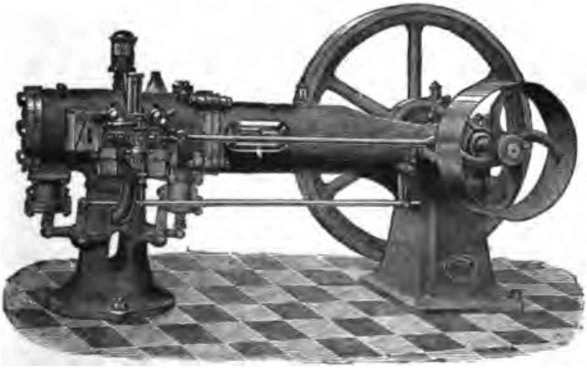
The indicator card, shown full size in Fig. 121, as taken from this engine, gives the curves traced throughout three explosions. The waves on the expansion curve are obviously due to the vibrations of the light spring used.

When running at 180 revolutions per minute, this engine gave 6 horse power on the brake, and consumed 180 cubic feet of gas per hour.

## Griffin Gas Engine.

The *three-cycle type* of gas engine affords a striking example of the many variations possible in the order of operations in the cylinder of the internal combustion engine. To this type belongs the Griffin engine, Fig. 122, which is double-acting with the cylinder closed at both ends as in an

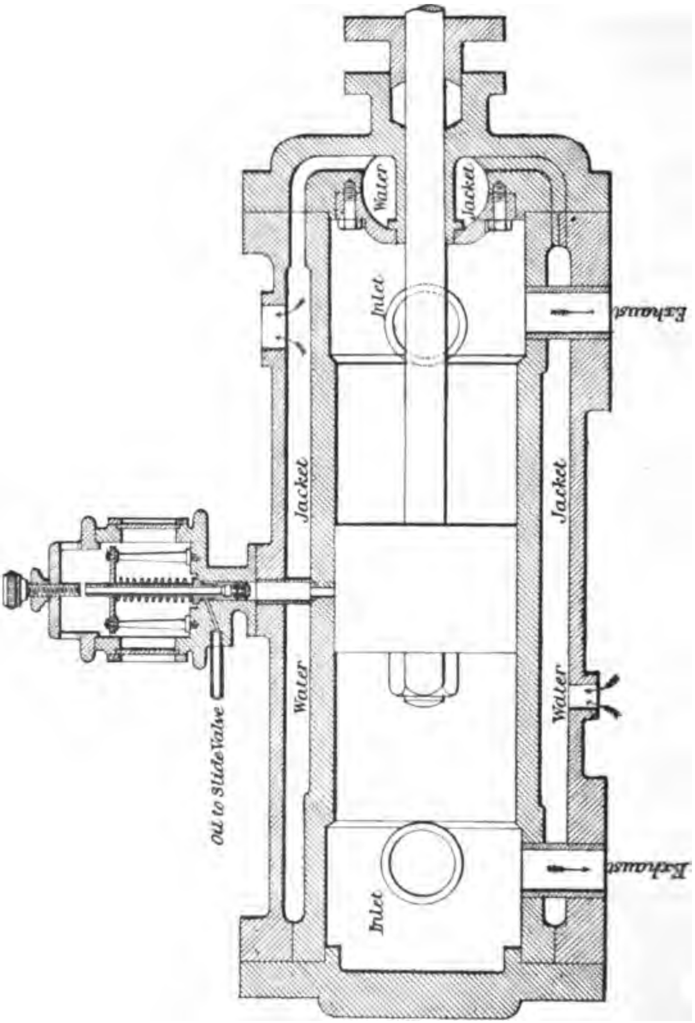
FIG. 122.



GRIFFIN DOUBLE-ACTING ENGINE.

ordinary steam engine. The charge of gas and air is fired alternately on each side of the piston once every three revolutions, and thus gives one impulse to the piston every one and a half turns of the crank shaft.

FIG. 123.



GRIFFIN DOUBLE-ACTING CYLINDER (SECTIONAL ELEVATION).

The admission and exhaust valves are conical disks of the lifting type held on their seats by spiral springs, and opened by cams on a side shaft, which is driven in the usual way by worm gear from the crank shaft. The two gas inlet valves are on the same side and at each end of the cylinder, whilst the two exhaust valves are similarly placed on the other side.

The drawing, Fig. 123, of the cylinder shows the *water-jacket*, *lubricator*, ports, and piston.

The *water-jacket* around the piston-rod is necessary to prevent overheating. This rod has to pass through a burning charge in the front end of the cylinder, the temperature of which is probably not less than 1400° to 1600° Centigrade. This would speedily raise the temperature of the rod so as to destroy all lubrication and packing. Not only is the water-jacket effective in preventing overheating even during a long run, but the cooling surface of the rod considerably reduces the mean effective pressure during combustion in the front end of the cylinder. In the motor trials by the Society of Arts (1888–89) the pressure at the back of the cylinder in the Griffin engine was from 6 lb. to 14 lb. higher than in the front, doubtless in a great measure due to the influence of this extra cooling surface of the piston-rod.

The *lubrication* of the piston is effected by the device shown above the cylinder in Fig. 123. Since the cylinder is closed at both ends, the ordinary method of dropping oil on the piston at the open end of the cylinder will not do, and it is essential that while feeding the oil into the interior of the cylinder through a closed passage, no products of combustion should be allowed to enter the oil in the lubricator, as such would produce a black viscid precipitate, and thus destroy its operation.

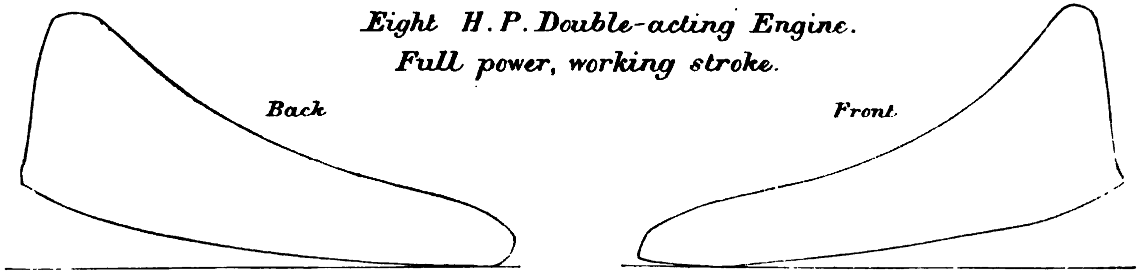
The *ignition* is by flame and plain slide-valve with a small chamber containing gas under pressure.

Whenever the engine is running overspeed the *governor* completely cuts off the supply of gas, causing one or more explosions to be missed until the speed is reduced to its normal value, about 200 revolutions per minute.

The cycle of the Griffin double-acting engine may be seen

FIG. 124.

Eight H.P. Double-acting Engine.
Full power, working stroke.

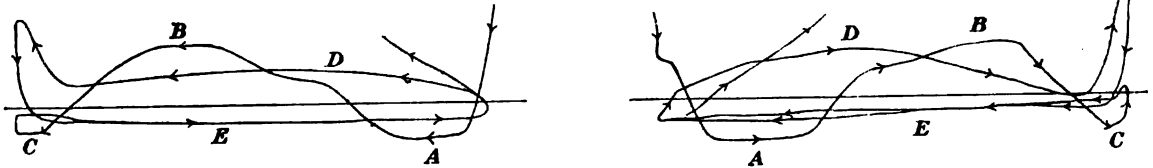


Revs. per min. = 223·2.
Mean press. = 59·25.
Scale. $\frac{1}{100}$.

Revs. per min. = 223·2.
Mean press. = 55·75.

FIG. 125.

Full power, pumping stroke.



Mean-press = – 3·80
Scale. $\frac{1}{10}$.

Mean press = -3·0

INDICATOR CARDS FROM GRIFFIN DOUBLE-ACTING ENGINE.

by the two sets of *indicator cards*, Figs. 124 and 125, taken from both ends of the cylinder.

The order of operations at each end of the cylinder is as follows:—Drawing in the combustible mixture of gas and air, compressing this charge, ignition and explosion, ejecting the products of combustion, drawing in a scavenger charge of air, and ejecting this scavenger charge of air.

In Fig. 120 the compression and explosion strokes are given, whilst Fig. 125 shows the variation in pressure during AB *exhaust* of residual products, C suction, and D sweeping out *scavenger* air, and E *suction* of combustible charge at a pressure of 1 lb. per square inch below atmosphere. These two pumping strokes represent work done *on* the gas *by* the engine, and the mean pressure 3·54 lb. per square inch must be deducted from the mean pressure during working stroke to give the mean effective pressure exerted *by* the gas *on* the piston.

These diagrams were taken by Professor Kennedy in a series of trials at Kilmarnock, in which he found the gas consumption at full power, 23·6 cubic feet per brake H.P. per hour; whereas careful tests with this engine using London gas show the total consumption, including gas for ignition, 28·56 cubic feet per brake H.P. per hour. The mechanical efficiency is 81 per cent., and the gas consumption 23·1 cubic feet per indicated H.P. per hour.

This engine runs very steadily, with extremely slight fluctuation in speed under widely varying loads, and excellent results are obtained by driving dynamos for electric lighting, without any appreciable blinking or unsteadiness in the light from the glow lamps.

The **Griffin Twin Engine** consists of two single-acting cylinders placed side by side, and working with this particular cycle. Since each cylinder gives one explosion every three revolutions, the two cylinders give an explosion every one and a half revolution, so that when the cranks are set half a revolution (180°) apart, the impulses alternate in each cylinder at equal intervals.

FIG. 126.

Two H. P. Twin engine.
Full power, working stroke.

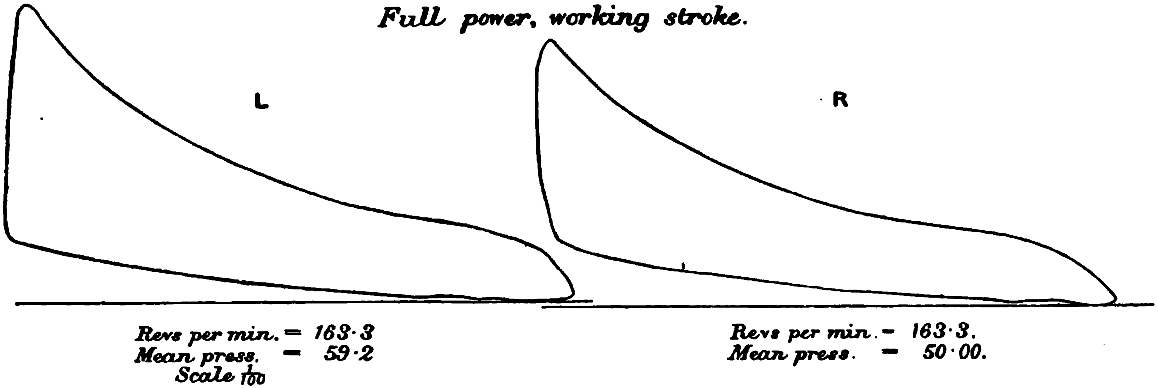
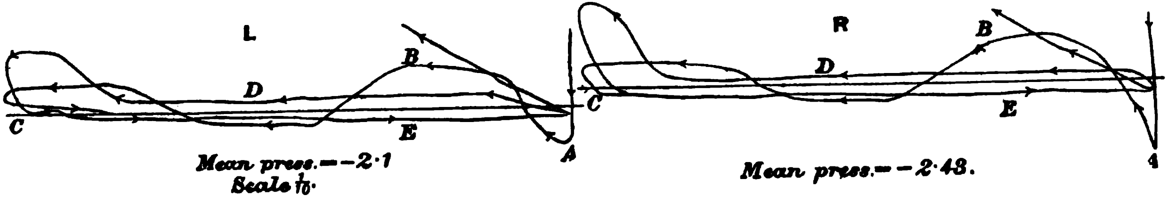


FIG. 127.

Full power, pumping strokes.



INDICATOR CARDS FROM GRIFFIN TWIN ENGINE.

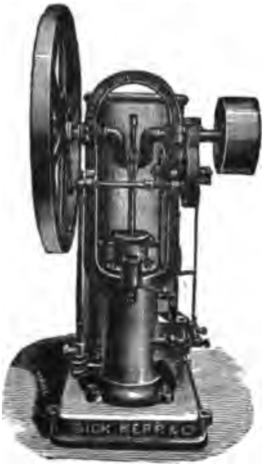
By this construction the reciprocating parts are well balanced.

The admission of gas to the two cylinders, and the ignition is effected by one slide valve, the two exhaust valves being opened by one cam.

The indicator cards, Figs. 126 and 127, are samples taken by Professor Kennedy from the left and right hand cylinders of this twin engine, when the gas consumed was about 23·8 cubic feet per indicated H.P. per hour.

There is also a small engine, one H.P., single-acting vertical type, Fig. 128, of very simple construction.

FIG. 128.

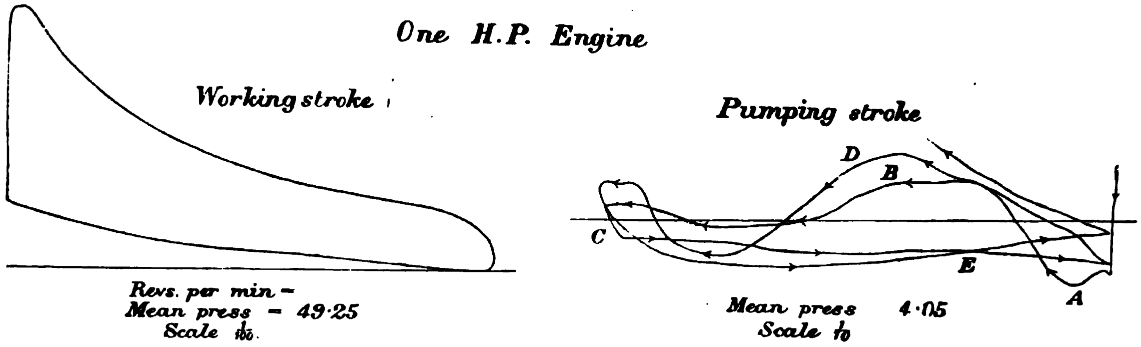


VERTICAL GRIFFIN ENGINE.

It has one gas valve, slide, and exhaust valve; the cycle is the same as given above.

The indicator cards, Fig. 129, show the operations in this single-acting cylinder. This handy little engine runs quietly, though not with the same uniformity in speed as the other types of Griffin engine, and it will be found useful for many purposes requiring only small power.

Fig. 129.



Indicator Cards from Single-acting Engine.

The gas consumption is 35 cubic feet per brake H.P. per hour.

The Griffin engine is made by Messrs. Dick, Kerr, and Co., Kilmarnock.

## CLASS II.

### SECOND TYPE.

Here a combustible mixture of gas and air is drawn into a pump and compressed, during the return stroke, into a reservoir at a pressure from 40 to 80 lb. per square inch above the atmosphere. Then the mixture is allowed to pass into a cylinder, being gradually ignited as it enters, *without rise of pressure.* At first the burning gases expand, *at constant pressure*, driving forward the working piston through half its stroke; the second half is effected by the adiabatic expansion of the hot gases to double their volume. The return stroke of the motor piston discharges the burnt products, at atmospheric pressure, into the exhaust.

Thus the cycle of this type of internal combustion engine consists of the four following periods:—

1. *Compression* of the charge of gas and air along an adiabatic up to the pressure of combustion or burning.
2. *Slow combustion* of the mixture *under constant pressure* until cut-off occurs.
3. *Expansion* along an adiabatic.
4. *Exhaust* or rejection at atmospheric pressure.

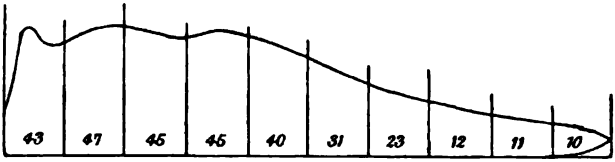
### **Brayton Engine.**

In 1872, BRAYTON patented in this country, an engine which he had at work in America.

It was designed on a most important principle. There is no explosion, properly so called, but the mixture of air and inflammable vapours, under pressure in a reservoir, is ignited and burns slowly at constant pressure as it enters the motor-cylinder where the burning gases expand doing work. Instead of ordinary coal gas or lighting gas, this engine uses volatile *hydro-carbon vapours derived from petroleum*, naphtha, and other light inflammable oils.

A mixture of 12 vols. atmospheric air to 1 vol. vapour of petroleum, is pumped, at a pressure of about 60 lb. per square inch, into a strong iron vessel or reservoir fitted with safety valve and pressure gauge. At the beginning of the out-stroke a valve opens and allows some of the gaseous mixture to pass through layers of wire gauze (called an "interceptor") which, as in the safety lamp, prevents explosion but ignites the gas, *without rise in pressure*, as it enters the cylinder and expands driving forward the piston. In the return stroke the piston drives out the products of combustion.

FIG. 130.



CARD FROM MOTOR CYLINDER: BRAYTON PETROLEUM-ENGINE.

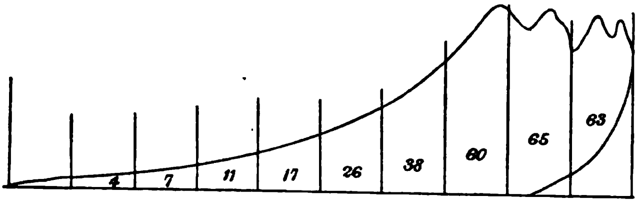
Area of piston, 50·26 inches; stroke, 12 inches; Mean pressure, 30·2 lb.

The indicator card, Fig. 130, was taken by Mr. Dugald Clerk from the motor cylinder of an American Brayton engine running at 200 revs. per min. and using petroleum of specific gravity 0·850. It shows how the pressure is sustained as the ignited gases enter the motor-cylinder in flame. The pressure does not rise after ignition, only increase of volume takes place. At about the middle of the stroke the supply of flame is cut off, and the stroke is completed by the expansion of the enclosed heated gases. We must deduct the negative work indicated by the compression-pump card, Fig. 131, from that found by motor card, to get the available indicated power, 5·39 H.P.

Now, 1·378 gallons of petroleum were burned in one hour;

that comes to 0·255 gallons or 2·16 lb. per indicated H.P. per hour.

FIG. 131.



AIR-PUMP DIAGRAM: BRAYTON PETROLEUM-ENGINE.

Area of piston, 50·26 inches; stroke, 6 inches; mean pressure, 27·6 lb.; pressure in reservoir, 60 lb.

Much better results were expected of this engine judging by its cycle. However, undue throttling and resistance of valves and air-ports, combined with prolonged cooling action of the cylinder walls, greatly reduced the practical efficiency of the Brayton engine.

## Siemens Regenerative Engine.

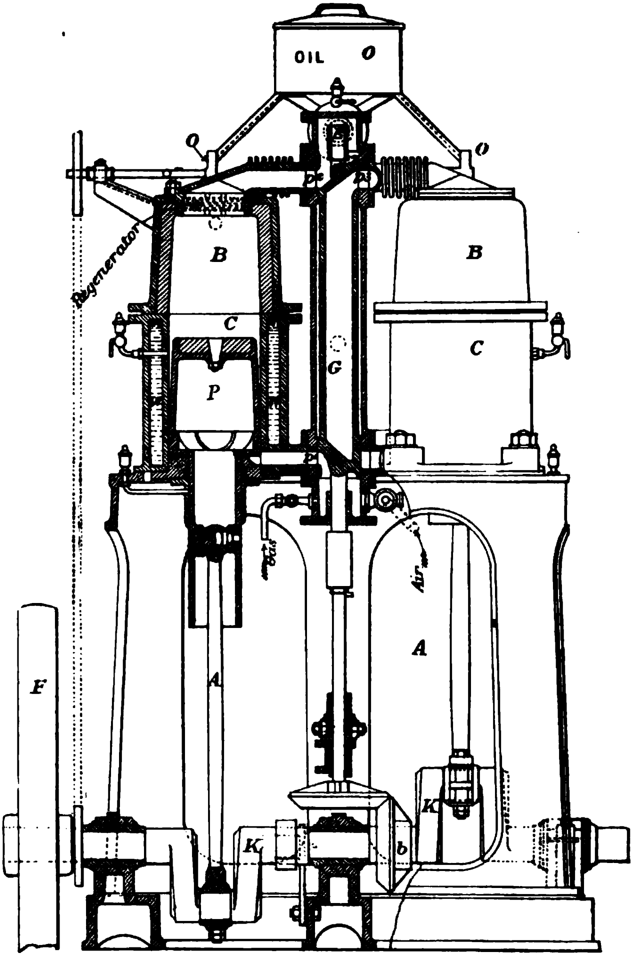
This method of compression was by no means new. As we have seen above, p. 149, in 1860, Sir WILLIAM SIEMENS had worked it out in his hot-cylinder engine, in which the gases are pumped into a receiver under high pressure, and heated by passing through regenerators before being ignited as they enter the furnace or heating cylinder, and the combustion is produced gradually. Then the gases, after having served to propel the working pistons by their expansive action, are discharged through regenerators, which absorb the heat and give it to the incoming fresh charge before it is fired.

The latest regenerative engine designed by Sir William Siemens in 1881, is very simple, and, from theoretical considerations, should give highly efficient results.

In it we find a *regenerator* or economiser of heat, a *differential piston*, and a simple but *certain mode of ignition* for gases of low inflammability by the electric spark.

Fig. 132 a front and Fig. 133 an end elevation, both partly in section, give a good idea of this engine, which comprises two motor pistons connected by rods A to the cranks K set 180° apart on the motor-shaft E which carries the fly-wheel F.

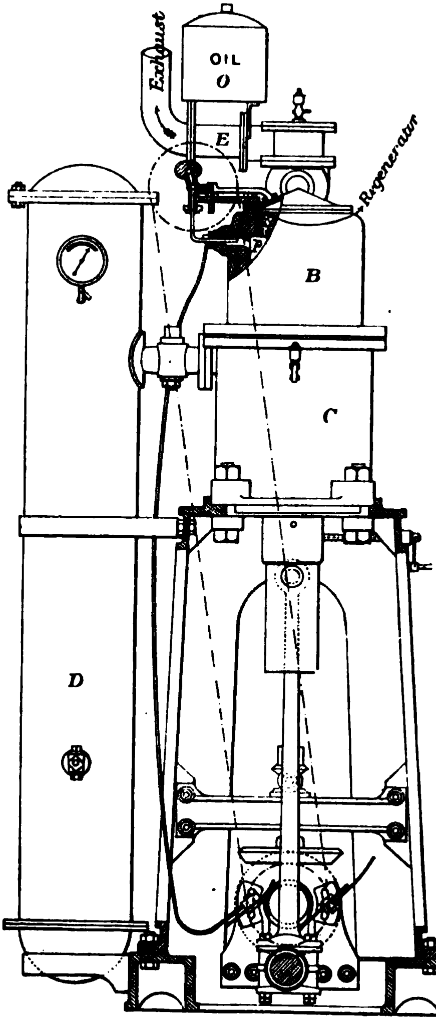
FIG. 132.



SIEMENS ENGINE.

The trunk-piston P is hollow, and its upper face is covered with a shield of plumbago or fire clay to protect the lower part of the cylinder and packing from heat. This is surrounded by

FIG. 133.



SIEMENS ENGINE.

water-jacket W, whilst the upper part B of the cylinder is lined with fire-clay or other refractory material.

The combustible mixture of gas and air is compressed, through cock H, into the reservoir D.

Distribution is effected by a *hollow cylindrical slide* G, situated in a casing between the two cylinders, revolving synchronously with the motor shaft, being driven from it by the bevel gear *b*. Gas and air are admitted by the stop-cocks, *g* and *a*, into this casing, which communicates, by the annular passages $p^1$ at the bottom and $p^3$ at the top of the slide, with each of the cylinders alternately, and by $p^2$ at the top of the slide with the exhaust E.

Before entering the cylinder above the piston the charge passes through the regenerator, which consists of wire gauze screens or pieces of metal.

The *ignition* is effected by a dynamo on the crank-shaft giving the electric spark at *p*, Fig. 133, within the cylinder B, on a very inflammable mixture obtained by a few drops of petroleum or volatile hydrocarbon oil carried from the vessel O by the pipes *o*, and deposited by revolving hollow plugs on the first portion of the charge when it is heated in passing through the regenerator.

The *cycle of operations* in each cylinder is as follows:—

Starting with the piston, P, in its lowest position, as shown in Fig. 132, the burnt products of the previous charge in B are free to escape, through the regenerator R and the passage $p^2$, to the exhaust E.

During the up-stroke, the piston P draws in the combustible mixture of gas and air through *g* and *a*, at the same time that it ejects by its upper face the burnt products through the regenerator R, to which they give up a large portion of their heat, before escaping by the exhaust E.

At the end of the up-stroke, the revolving slide G establishes communication between the reservoir D and regenerator. A portion of the compressed charge, enriched by the hydrocarbon oil from O, and heated by the regenerator, is ignited within the cylinder by the electric spark, and ignites the rest of the charge as it enters the cylinder. The burning gases largely expand in volume; but the pressure remains the same as that in the reservoir D, and acting on the full upper area of the piston, drives it down. When the piston has performed part of its down-stroke, the supply of gaseous mixture is cut off by the slide G, and the contents of the cylinder at B expand at the expense of their own heat, propelling the piston.

But at the same time, during the down-stroke, the lower and annular face of the piston acts as a pump on the mixture drawn in during the up-stroke, compressing and forcing it through the opening in the revolving slide G into the compression reservoir D. The piston is thus driven down by a force proportional to the difference of the pressure on its two faces.

On the completion of the down-stroke, the exhaust passage is again opened by the slide, and the expanded products of combustion in B escape through the regenerator, which stores up most of their heat, and restores it to the next incoming charge.

Each of the pistons receives an impulse every revolution. A plan is also given of an engine having four cylinders working on one shaft, each pair working at right angles with a crank opposite to the crank worked by the other pair. This avoids dead centres. The engine promises to give good results, and indicates the stage reached by Sir William Siemens.

Doubtless in the application of the regenerator to the internal combustion engine lies the future development and success of gas engines for very large powers.

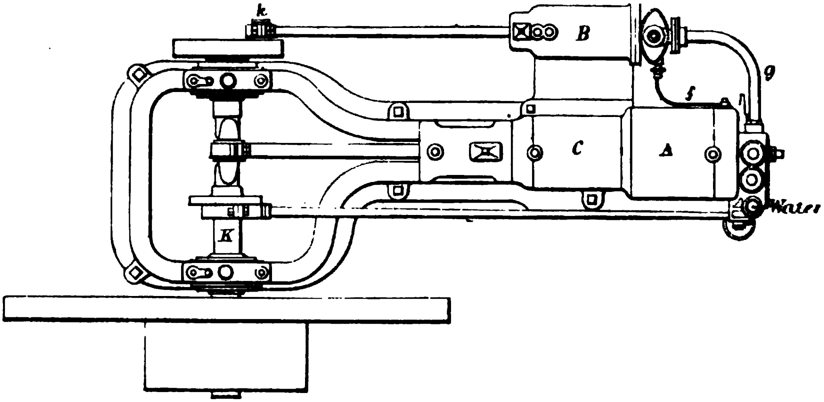
## Foulis Engine.

FOULIS, of Glasgow, has also tried hard to make engines of this type workable.

As usual, the explosive mixture is compressed by a pump, and ignited when entering the motor-cylinder. The dimensions of the pump and motor-cylinders, as well as the strokes of their pistons, are arranged so that the combustion takes place in the motor-cylinder under sensibly constant pressure equal to that in the pump.

In 1878, Foulis patented a gas or hydro-carbon engine, with three cylinders placed vertically above the driving shaft on which the three cranks are fixed each one-third of a revolution before the other, as in the tar and liquor pumps used in gas works. Above the cylinders there is a small combustion chamber, lined with refractory firebrick, where the gaseous mixture is ignited on its way into the motor-cylinder. The gases burn gradually and expand, driving the working piston. At first, the charge is fired by a jet burning inside a small platinum tube opening into the combustion chamber, but when the engine is at work, this chamber is kept hot enough to ignite the gases. The compressed charge passes through an annular orifice, varied at will by a screw and plunger, besides the regulator acting directly on the admission valve and the distributor, control the strength and quantity of the charge.

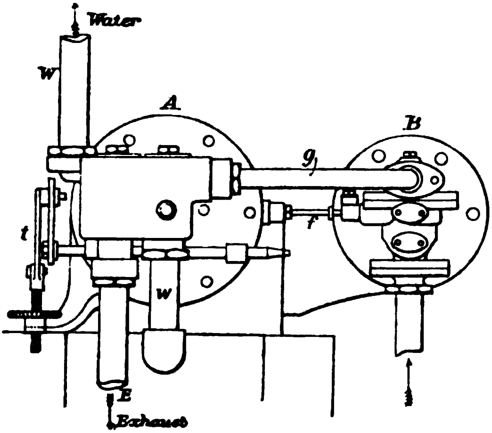
FIG. 134.



FOULIS ENGINE.

Fig. 134 shows a plan, and Fig. 135 an end elevation of the FOULIS improved horizontal engine, patented 1881. Part A of the large cylinder is lined with refractory material and metal cover forming the red-hot chamber where the gaseous mixture is burned. Part C is surrounded by cold water, and is the working cylinder. The piston is faced with refractory non-conducting materials.

FIG. 135.



END VIEW.

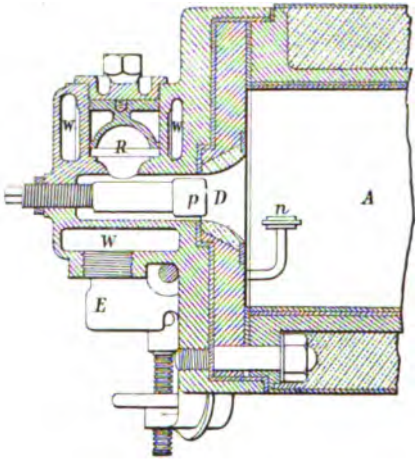
The pump B is driven from the main shaft K by crank pin *k*, to which the pump rod is attached, and which is put behind the engine crank at an angle depending on the difference in capacity of the pump and working cylinder, so that the compressed charge, when it passes into the larger volume of the working cylinder, and is expanded by heat, is under the same pressure as when in the smaller volume of the pump.

This pump forces the compressed mixture of gas and air by the pipe, *g*, inlet valve, L, through the wire gauze, R, Fig. 136, into the annular space, D, lined with refractory material which may be sufficiently heated to ignite the gas as it enters the hot cylinder, A.

By a small pipe, *f*, gas and air pass to the inlet chamber, D, Fig. 137, to ignite the mixture; but when the cylinder is heated this is done by the knob, *n*, of fireclay, asbestos, or platinum, inside the cylinder A, Fig. 136.

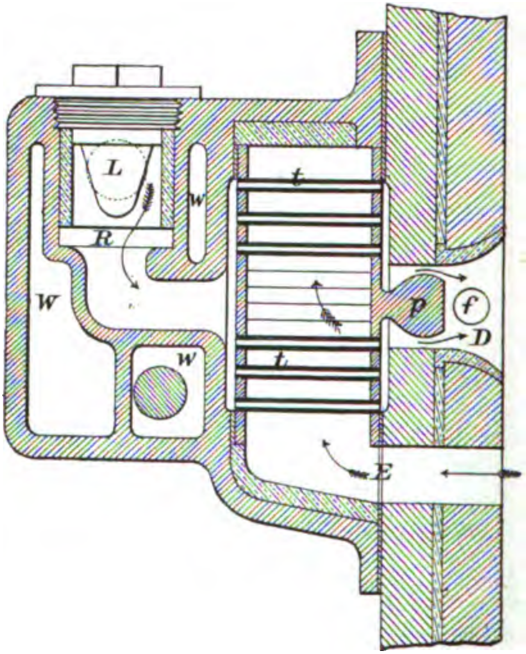
The chamber which contains the regenerator, R, is

FIG. 136.



COMBUSTION CHAMBER.

FIG. 137.



GAS PORTS AND REGENERATOR.

surrounded with water-jacket, W, to prevent the wire gauze being destroyed by the gases at too high temperatures.

The action of the engine is this :—

The combustible mixture is forced by the pump B through the layers of wire gauze R and the annular orifice D into the hot cylinder A. The combustion takes place gradually at constant pressure, only during one-third of the working piston stroke. After this the admission is stopped and the gases expand, driving on the working piston to the end of its stroke. On the return stroke the exhaust valve E is opened, by the lever, tappet, and eccentric arrangement, Figs. 135 and 137, but closes near the end of this stroke, when a portion of the burnt products is compressed until overcome by the pump B forcing the fresh charge through the inlet valve L.

Before being allowed to escape, the products of combustion circulate round the fireclay or refractory tubes *t*, Fig. 137, through which the fresh charge passes immediately afterwards from the pump into the hot-combustion chamber A. In this way part of the heat usually carried away and lost by the exhaust is utilised, being communicated by means of the refractory tubes to the incoming gases before combustion takes place. Also, by burning the gas in a red-hot chamber A lined with refractory material, conduction of heat through the walls of the cylinder may be partly prevented, so that if the temperature of rejection can be sufficiently lowered, this machine will be highly efficient.

However, many difficulties arise with gas engines in actual practice which are not apparent when considering the designs on paper, and which have hitherto prevented the realisation of the good results to be expected from such an engine working with this cycle.

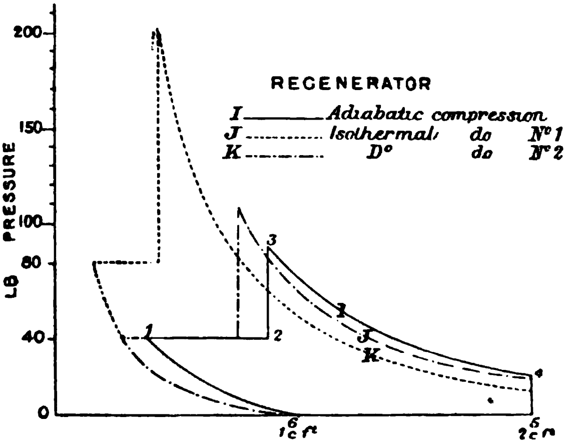
## Ideal Regenerative Engine.

Professor Fleeming Jenkin, in his paper before the Institution of Civil Engineers, considered an ideal engine in which the fluid is simply passed in and out through a regenerator.

That is, he proposed to take the gas and air through a regenerator into the cylinder so as to heat them before ignition, and instead of rejecting the residual products directly into the air, to cool them by passing out through a regenerator.

The indicator diagrams, Fig. 138, have been calculated for such an ideal engine. Starting at the point 6 on the lower horizontal line in the small diagram I, one cubic foot of fluid is compressed in a pump without gain or loss of heat up to a pressure of 40 lb. above the atmosphere. Then the fluid is supposed to be displaced at constant pressure, as indicated by the horizontal line 1, 2, passing through a regenerator heated by the previous charge. Meanwhile the temperature rises, and the fluid expands, doing work until 17·5 British thermal units have been restored by the regenerator.

FIG. 138.



IDEAL INDICATOR DIAGRAMS.

Then 19·2 thermal units are added, by combustion at constant volume, to raise the temperature to 1537° C., whilst the pressure rises from the point 2 to 3. Now the fluid is allowed to expand, from 3 to 4, along the curve I, without gain or loss of heat, until it occupies two cubic feet, or twice its volume at the beginning of the cycle. The fluid is then expelled through the regenerator, to which it gives more than 17·5 British units of heat. Calculation of the theoretical efficiency from the diagram I shows that an engine working with this cycle would convert 56 per cent. of the total heat of combustion into indicated work.

The diagram J is calculated on the assumption that heat is abstracted in the compressing pump, so that the temperature of the fluid remains constant during compression. In this case the same quantity of heat, 17·5 British units per cubic foot of original fluid, is stored and restored in the regenerator. This gives a theoretical efficiency of 54 per cent.

The largest diagram K shows the effect of isothermal compression to 80 lb. per square inch above the atmosphere, using the regenerator as before. The efficiency of such an engine would be 72 per cent. In all these cases the heat rejected with the fluid at end of the stroke, added to the heat converted, is equal to the whole heat of combustion during each stroke.

The regenerator can only store up as much of the heat left in the rejected fluid when the exhaust opens as will cool this to the temperature of the fluid entering from the pump. Practically, the whole of this heat could not be restored. Of course the temperature of the incoming gases cannot be raised by the regenerator above that to which the previous charge was reduced by expansion in the motor cylinder.

If such an engine could be constructed, the efficiency would be very high, and the pressure pretty uniformly distributed throughout the stroke. Still, a large proportion of the heat would pass through the walls of the cylinder. Some such arrangement seems necessary to save part of the heat now taken away by the cold water-jacket round the cylinder, as well as that rejected with the products of combustion by the exhaust and completely wasted.

Consequently, we find **numerous devices** have been proposed by which the *waste heat* rejected in the exhaust gases and cooling water may be *utilised to gasify or vaporise the oil supplied*, in small powers of modern petroleum or liquid hydro-carbon engines; instead of the more expensive but also more economical arrangement of separate gas generator or producer used with large engines.

### Simon Gas and Steam Engine.

Messrs. SIMON, of Nottingham, use slow combustion, and adopt the plan of passing steam into the motor cylinder for the double purpose of helping to drive the piston by its expansion and at the same time to act as a lubricator by keeping the cylinder moist. However, the novel idea lies in *utilising the heat*, otherwise lost through the walls of the cylinder, as well as by the exhaust products, *to generate steam* for this purpose.

Fig. 139 is a sectional elevation; the fly-wheel and driving-shaft are not shown, but the cranks are set at ¼ centres. This engine is also built horizontally.

The little piston D, in its down-stroke, draws the mixture through a valve T into the pump cylinder B. The slide S admits the gas from *g*, and air supplied by *a*. In the return stroke D drives this mixture through a valve N into the reservoir or envelope A.

From this the compressed charge passes by L and the admission slide S′, through wire gauze into the working cylinder above the piston P.

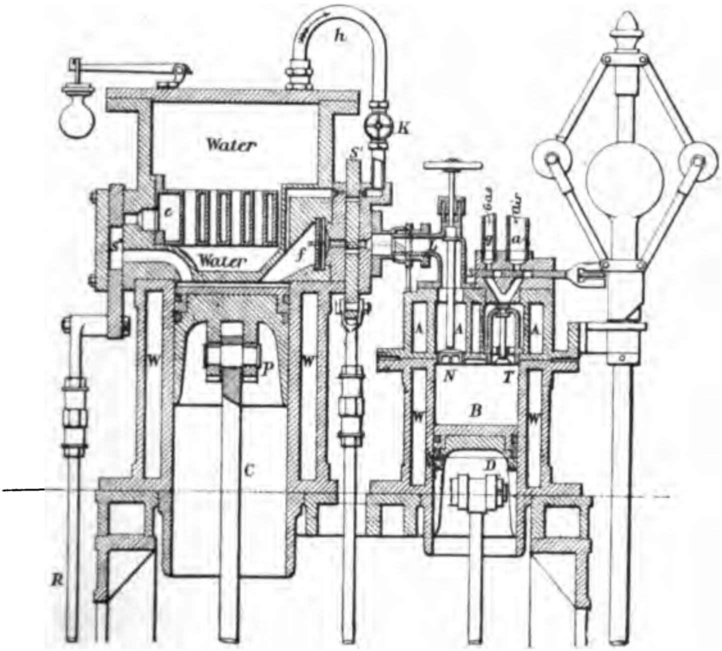
Here the mixture is ignited *at constant pressure* by a flame *f* kept burning in front of the wire gauze, which prevents the flame spreading into the reservoir. This permanent burner is supplied from a small receiver into which some of the compressed mixture is allowed to pass. The compressed charge is thus *gradually burned* on entering the working cylinder.

When a sufficient quantity has entered, the slide S′ closes the inlet, and the combustion products expand, driving the piston P, and performing work.

In the return stroke the burnt products are expelled by the slide-valve S″ to the left, into the open air through the worm *e*, surrounded by water, which also cools the cylinder.

The water soon becomes heated, and when the steam generated attains a pressure of 3 or 4 atmospheres, the cock K admits during each stroke, through the slide S″, a certain quantity of the steam into the motor cylinder, where it expands, helping the gaseous mixture to drive the piston, acts as a lubricator, and cools the cylinder so that little oil is required.

FIG. 139.

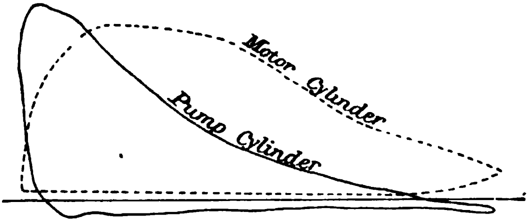


SIMON ENGINE.

The centrifugal governor regulates the admission of gas and air by a cam acting on the slide-valve S. The proportion of the combustible mixture is 1 of gas to 10 of air.

Fig. 140 shows the indicator cards from this engine when making 146 revolutions per minute. The motor-cylinder diameter 9·25 inches, length of stroke 15·75 inches, and the mean effective pressure by diagram is 22 lb. per square inch, indicating 7·7 horse-power.

FIG. 140



INDICATOR CARDS FROM SIMON ENGINE.

The pump cylinder diameter 7·2 inches, length of stroke 9·84 inches, and mean pressure 16 lb. per square inch; indicating 2·1 horse-power.

The difference 5·6 is the real indicated horse-power, whilst the brake was 4·2 horse-power, giving mechanical efficiency of $\frac{4 \cdot 2}{5 \cdot 6} = 0 \cdot 75$.

The gas consumption is 50 cubic feet per brake horse-power per hour. This has been reduced to 22 cubic feet per indicated horse-power per hour.

The use of steam, although at first sight an advantage, not only produced great cooling effect in the motor-cylinder, but also added too many parts to the engine, so that it became too costly to build, and the manufacture was therefore not continued.

This engine has given place to an ordinary compression engine (page 191) of more compact and less complicated construction, the pump and motor pistons being replaced by one double-headed piston which performs the same functions in a first type cycle.

# CHAPTER VII

## METHODS OF FIRING.

AN internal combustion engine is not properly fitted to work safely and regularly without some perfectly certain means of igniting the charge. This is of primary importance, because upon the certainty of ignition largely depends the regularity of running, as well as the economy in gas consumption.

The explosive gaseous mixture in the engine cylinder is usually ignited by one of three simple methods: (1) a *gas flame* may be brought into contact with the charge; (2) the *electric spark* from an induction coil may be made to play, *either intermittently or continuously*, between two platinum points, and through the mixture; (3) a *thin tube or platinum wire* may be *heated to incandescence*, the former by a gas flame and the latter by electricity, part of the charge being brought into contact with the incandescent metal.

Besides the various combinations of these methods of ignition, a few other plans have been proposed, though not successfully carried out in practice.

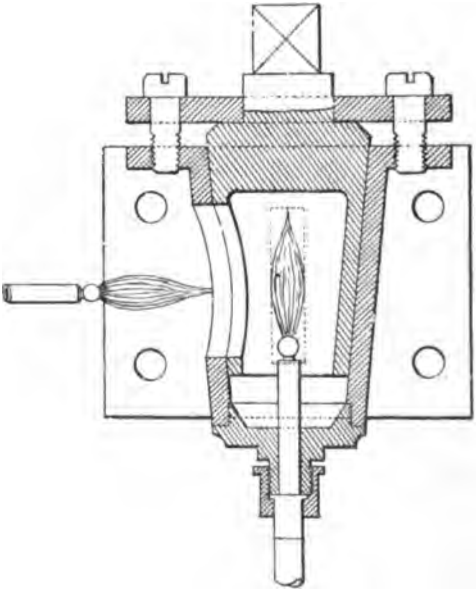
### (1) **Ignition by Flame.**

The igniting flame, lighted by a gas burner outside the cylinder, is generally carried in a slide-valve up to the explosion port, in order to fire the charge in the motor cylinder at any desired moment. The ignition of a *compressed* mixture of gas and air presents many difficulties, especially when it is to be repeated with certainty and regularity from 80 to 100 times per minute. The violent inrush of gas under pressure is likely to blow out a feeble flame unless the igniting chamber carrying this flame is large enough to allow of free circulation, whilst part of the compressed charge is admitted *gradually*, somehow, to make the flame stronger and increase the pressure in the igniting chamber before it opens to the explosion port of the cylinder.

*Street's Igniting Slide-valve.*—The first crude suggestion of this mode of igniting the charge in a gas-engine cylinder was probably that made in 1794 by *Robert Street*, who proposed a slide-valve containing flame to ignite the combustible mixture through a touch-hole.

*Barnett's Igniting Cock.*—The system of flame ignition, at present in use, at first appears in the Patent Specification, No. 7615 of 1838, by *William Barnett.* The igniting apparatus consists of a conical cock, sectional elevation Fig. 141, into which is closely fitted a hollow revolving plug containing

FIG. 141.



BARNETT'S IGNITION COCK.

a gas burner. This small gas jet inside the plug is lighted by an external flame through a port in the cover, as shown at the side. There is one other port in the cover opening to the motor cylinder at the back. The hollow plug has only one side-aperture, which, in the position shown in Fig. 141, opens to the atmosphere, allowing free circulation of air through the plug, so that the outside flame ignites the inner gas jet. As the plug is turned on, the opening is completely closed by the cover, and the flame is kept alight in it until the opening in the plug comes opposite the explosion port in the cylinder. Part of the compressed charge of gas and air then enters the hollow plug, which must have sufficient space inside for the gas to circulate around the small flickering flame, strengthen and spread the flame rapidly, thus firing the charge in the motor cylinder. The explosion usually extinguishes the flame in the hollow plug which remains closed when further turned until it opens to the atmosphere by the lighting port, where the inside burner is again lit by the outside flame. The hollow plug is also cleared of the residual products by the free circulation of the air whilst it is open to the atmosphere. As before, the internal flame burns quietly until the plug is turned round with its slit opposite that in the cover and the explosion port, when the fresh charge is fired. The outside flame must be protected from draughts of air; for if blown aside it may fail to relight the flame inside the plug, consequently the charge would not be ignited, and the engine would soon be brought to a standstill.

*Hugon's Slide Ignition Valve.*—The method of ignition by flame was first successfully used with a *plain slide-valve* in the Hugon engine of 1865.

This engine, as above described at page 146, is double-acting, with admission and exhaust valves arranged as in the ordinary steam engine. The inner slide is provided with five ports altogether; namely, one exhaust and two admission ports, besides the two igniting chambers—one near each end.

In each of the igniting chambers there is a burner supplied with gas under slight pressure by a separate pipe from a bellows pump, so as to shoot the flame well into the explosion port and afterwards expel the residual products of combustion from the gas pipe when the internal slide flame is extinguished by the explosion in the cylinder.

Two ordinary gas flames are kept burning outside, one close to each end of the cylinder, so as to come in contact with and relight the gas jets in the igniting chambers of the slide as it moves in and out. If, through any cause, either of these outside flames fails to relight the gas jet in the slide every revolution, then the charge is not fired.

The slide is liable to be heated to a high temperature by the two interior and two exterior flames, which burn the oil on the slide faces and thus tend to destroy lubrication. There is also trouble in keeping the slide ports clean and free from burned oil and incrustation of carbon.

However, by frequently cleaning the slide and ports, as well as by careful attention to lubrication, this method of igniting by slide carrying burners supplied with *gas under pressure* is reliable, because a considerable portion of the charge is inflamed at once by contact with the large surface of the flame shooting into the gaseous mass, thus starting the combustion of even a weak mixture with certainty.

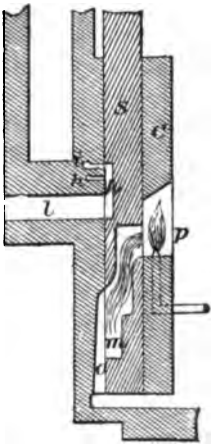
Various modifications of this method have been successfully used in other engines. Gas and air mixed in the proper proportion are compressed into the igniting cavity in the slide, the pressure being nearly equal to that of the explosive mixture which is then readily ignited by the flame in the slide cavity.

*Otto's Slide-valve Ignition.*—The next important modification of igniting valve is the Otto. A small quantity of gas and air is admitted into a cavity in the slide and ignited by a constant flame kept burning in the slide cover. The burning is slow with a blue flame, and soon the slide is moved, cutting off all communication with the outer air whilst the glowing mass is carried in the slide to be partially sucked into the explosion port, thus igniting the charge in the atmospheric engine.

However, in the modern engine, if this feeble flame were brought at once into contact with the *compressed* mixture, it would be extinguished by the sudden inrush of gas. But this is prevented by the ingenious device of the equilibrium port: a small hole at the top of the ignition port admits a portion of the compressed mixture from the motor cylinder to revive the flickering flame and gradually increase the pressure in the cavity of the slide before it is brought opposite the main explosion port, when the flame shoots into and fires the compressed charge.

The igniting slide-valve arrangement in the Otto and Langen free-piston engine is shown in section Fig. 142, also in Fig. 100, page 154. It is by the port *k* in the slide that the mixture of gas and air, fed by the supply ports *i* and *h*, reaches the passage *l* and is sucked into the motor cylinder by the piston in its upward motion. At the same time the slide S is in its lowest position, and the ignition chamber *m* is filled from the gas pipe *o* with a mixture of gas and air which is ignited by contact with the gas flame *p* kept constantly burning in the slide cover C. As the slide S moves upwards, the chamber *m* is completely closed by the slide cover, and thus the glowing mass of gas in *m* is quickly brought opposite the explosion port *l* and ignites the rich mixture. The slide moves further up, keeping the gas port and cylinder closed during the explosion.

FIG. 142.

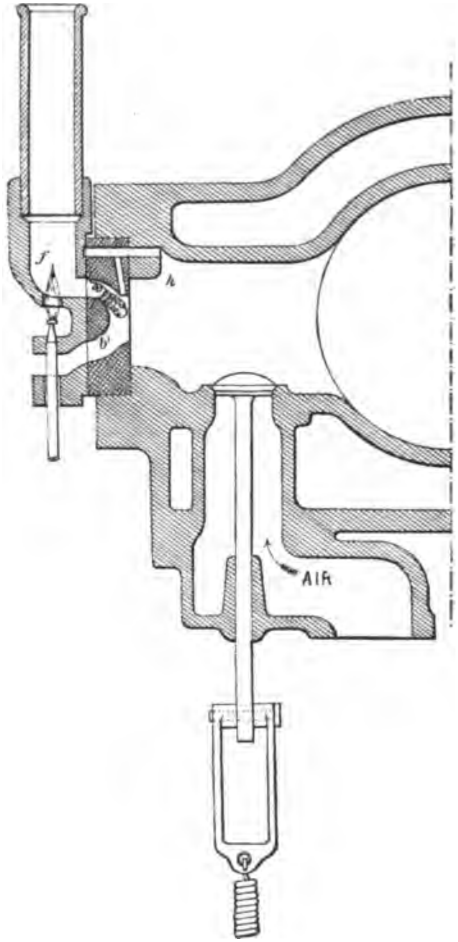


OTTO AND LANGEN IGNITING SLIDE-VALVE.

The large cavity in the slide seriously reduces the thickness of metal and increases its liability to buckle by the heat of the flame, and so spoil the sliding surfaces. The improved Otto igniting slide-valve has been described above in Chapter II.

Messrs. Crossley have from time to time modified this method of ignition to make it more reliable under different circumstances. When cheap fuel, as water gas, is used in the engine with high compression, ignition becomes difficult, and

Fig. 143.



Anderson and Crossley Platinum Wire Igniter.

the arrangement in Fig. 143 makes it more certain and regular. This is simply a combination of the flame and incandescent wire methods. A small spiral of platinum wire is fixed in the igniting chamber *b'*. The wire being kept at a red heat by the gas flame in the chamber *b'*, when ignited by the slide light *f* remains incandescent, and readily inflames the portion of the compressed charge which enters first by the small hole and forked passage *h* before *b'* opens to the main explosion port. This revives and strengthens the flickering flame in *b'*, at the same time establishing equilibrium of pressure between the gases in the motor cylinder and slide cavity *b'*, enabling the flame in the latter to ignite the whole charge. Slide igniting valves, in careful hands, are slow but sure in action, and have done good service. Still there are many grave objections to be urged against their general application, and which have induced Messrs. Crossley to abandon them in favour of hot tubes for some of their engines.

The slide itself is a delicate piece of apparatus, requiring accurate adjustment and careful handling. Its numerous and complicated orifices soon become incrusted and choked up with carbon from the gas flame, so that, however carefully the edges of the ports are set, the delicate operation of conveying the flame may be delayed—the flame may be burnt out before reaching the charge, or from premature extinction due to want of equilibrium of pressures, and result in miss-fires. A rich gas like ordinary lighting gas is clean and easy to light, but cheap fuel gas is more troublesome as it quickly fouls the ports, and requires a much stronger flame to ignite it with certainty. Besides, the slide light and the conveyed flame raise the temperature and tend to burn the oil on the slide faces. If the oil supply be neglected or dirt allowed to fall on the working surfaces, the slide ignition valves may at any time during a run get cut and so scored as to stop the engine. Such slides require to be faced up afresh. The slide surfaces must fit truly and press gently yet firmly against the cylinder, especially at the edges of the ports, else premature ignitions may occur to reverse the engine, or back explosions due to leakage may loosen the slide and cause serious injury.

## (2) **Ignition by the Electric Spark.**

The chemist is familiar with the use of the electric spark in gas analysis, and it has long been known that the passage of the spark through an explosive gaseous mixture causes some of the gases to combine with the oxygen present. The usual plan is to pass the electric spark between two insulated platinum points in the secondary circuit of a Ruhmkorff induction coil, the primary circuit being excited by the current from a battery either of Bunsen or bichromate of potash cells.

Usually in connection with the gas engine an interruptor or commutator of some sort serves to make and break the electric circuit at the proper time, and so induce the required spark.

However, instead of a battery, ***a little dynamo driven by the engine may be used to generate the electric current*** necessary to induce the spark.

In 1799, before much was known about the electric current, the ingenious French artisan Lebon, used static electricity to produce sparks and fire the charge of compressed gas and air alternately on each side of the piston. The electric influence machine was driven by the gas engine, and the electric sparks were only allowed to pass intermittently, being regulated to ignite the charge at the proper times.

Shepherd, in 1850, employed a dynamo machine to generate electricity for igniting the combustible mixture in the gas-engine cylinder.

Although such an important suggestion was made so early, yet this method of ignition does not seem to have come into general use, probably owing to the trouble given by the intermittent spark in the first Lenoir engine.

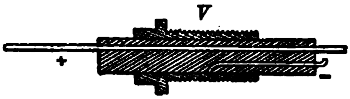
Doubtless, as the practical engineer becomes more familiar with dynamo-electric machinery, various simple magneto-electric arrangements will be devised whereby the gas engine will automatically generate the electric current, and, by means of a simple electric transformer, produce sparks to ignite its own charge.

Already some such arrangements have been described in patent specifications, and an example of this method of ignition in actual practice is afforded by the *Benz motor.* In this gas engine, ignition is effected by the electric spark between two insulated points, inside the cylinder, joined up in the secondary circuit of an induction coil. A little dynamo-machine, driven by a cord or belt from the fly-wheel, generates electric current for the primary circuit. The dynamo pulley has two grooves different in diameter; the smaller is used when starting to make sure that the speed of rotation of the armature coils in the magnetic field between the magnet poles is sufficient to generate electric current strong enough to induce the necessary spark. When the engine has got up speed the cord is shifted to the larger part of the dynamo pulley.

In this way the electric battery, so troublesome in the hands of the general public, may be dispensed with altogether.

*Lenoir's Electric Igniter.*—Lenoir used the electric spark method of ignition in his first commercially successful gas engine. The general arrangement has already been described at page 137. The *igniter,* Fig. 144, consists of a brass tube V, screwed into the end covers at the top of cylinder. This tube contains a plug of porcelain, or other suitable non-conducting material, to insulate the points of the platinum wires. The brass tube V makes metallic contact between the negative wire and the cylinder, thereby to that terminal of the induction coil. The positive wire passes through the insulating plug to be connected by binding screw and electric

FIG. 144.



LENOIR IGNITER.

leads to one segment of the commutator. The electric circuit is completed and the sparks passed between the platinum points to fire the mixture at the desired moment. Then the circuit is broken, and the spark does not pass until the next revolution of the engine, when the mixture is fired at the other end of the cylinder. In this way the spark is *intermittent.*

This arrangement has many weak points, and was found not to work well in practice. The ignition is irregular, sometimes taking place too soon, before the crank has passed the centre, and so tending to reverse the engine; at other times the ignition is much too late, considerably reducing the indicated power from a given charge; but too frequently the spark does not pass at all, and the charge is not fired. This is often due to the platinum points becoming short-circuited, that is, connected together either by a deposit of moisture between them, or coated with some of the oil used to lubricate the piston, or perhaps incrusted with carbon deposited during imperfect combustion of poor gas.

Such serious defects caused great trouble in the early Lenoir engine. In order to overcome these difficulties in the *Lenoir compression engine*, the electric igniter is placed at the top of the warm cartridge end of the cylinder close to the gas admission port, so that the platinum points are kept quite dry and free from oil, and surrounded with the richest part of the highly compressed and inflammable mixture.

This method of ignition is also used with success in the Priestman oil-engine, by making broad surface terminals, and very carefully insulating the wires whilst the explosive mixture of petroleum vapour and air is well heated and compressed before the electric spark is passed through it (see page 77).

Instead of an *intermittent* electric spark passed between two insulated points inside the cylinder at a given instant when a contact-maker completes the circuit of the exciting battery we find in the Simplex Motor a very effective method of ignition by an uninterrupted *stream of sparks* kept playing continually between two insulated points in a cavity of the slide-cover.

This *continuous* electric spark is sufficiently powerful to ignite with perfect certainty an explosive mixture even of cheap fuel gas under high initial pressure, and consequently allows of great economy in the consumption of gas per indicated H.P.

The arrangement is shown and described in Chapter III.

The combustion chamber in the motor cylinder communicates with the igniting chamber in the slide-cover by the admission port *i* and the oblique passage *j* in the slide-valve F. Before each explosion the burnt products are cleared out of this oblique passage *j*, through a horizontal groove in the slide opening to the outer air. When the edge of the slide-port *j* comes up to the admission port *i*, a small hole in the combustion chamber (like the equilibrium port in the Otto) coincides with the horizontal groove in the slide, and the compressed explosive mixture in the motor cylinder drives out the burnt products by the small hole, and is itself ignited at the same instant by the electric spark. In this way the instant of ignition is determined with great precision by the edges of the ports coming in line.

Instead of being the part of greatest nicety and delicacy, the slide now becomes a simple cast-iron plate in one piece with two holes: one for the admission of the fresh charge of explosive mixture, and the other for its ignition. It is not so much heated as a flame-carrying slide, hence lubrication is made easier and repairs needed but seldom.

Thus, whilst the tendency at present is to abandon the method of ignition by conveyed flame, and as the engineer is growing daily more familiar with electricity and its numerous applications, so ignition by the electric spark is again coming into favour, and proving not only satisfactory but also economical.

### (3) Ignition by Incandescent Metals.

*Incandescent Platinum.*—Various plans have been tried to raise metals to a red or white heat for the purpose of firing the combustible mixture in the gas-engine cylinder.

John Reynolds, in 1844, proposed to ignite the charge in his engine by a *thin platinum wire, heated to incandescence by the electric current from a voltaic battery.* A contact-maker, worked by the engine, completes the electric circuit, and sends the current to heat the wire at the proper times.

According to another method the wire is kept constantly at a red heat by the electric current, and brought into contact with the explosive gases by a slide-valve. In this case the wire is likely to get overheated and fused, either by too strong a battery current, or by the extra heat from the explosions. On the other hand, if the wire be not sufficiently heated by the current, the cooling action of each fresh incoming gaseous mixture may reduce the temperature of the thin wire below the ignition point, and so prevent the charge being fired at the proper moment. In unskilled hands an ordinary battery is also likely to give trouble in keeping it in proper working order. Although this method of ignition is well adapted to experimental researches, it has several disadvantages which unfit it for ordinary practical work. But the *spiral of platinum wire heated to incandescence by a flame,* as in Fig. 143, forms a useful auxiliary where ignition is difficult.

Mr. Dugald Clerk described in his patent, No. 3045 of 1878, and used an *incandescent platinum cage* in a compression engine the following year. The platinum cage is a rectangular box made of a great number of thin platinum plates fixed by rivets, and held apart by washers of platinum.

This grating is firmly fixed in a cavity of the slide-valve, and the platinum is *kept at a white heat by part of the flame from each explosion* passing through it out of the explosion port to a chamber in the slide cover.

*Hot-tube Ignition.*—In 1855 Dr. Drake, of Philadelphia, fired the charge of gas and air in his "ignition engine" by a thimble or cup-shaped piece of metal, 2 or 3 inches long, 1 inch internal diameter, and ⅛ inch thick. This cup is placed in a cavity of the cylinder, and *heated to incandescence by a blow-pipe flame outside.* At the proper time the piston uncovers the hole leading to this iron cup, and part of the mixed gas and air in the cylinder comes in contact with the heated surface, and becomes ignited. These igniters gave trouble, as they got rapidly burnt into a brittle state, and required frequent renewal.

Mr. Atkinson, in 1879, ignited the charge in his compression engine by a *wrought-iron tube* closed at the outer end, and having the open end screwed into a small hole drilled in the side wall of the cylinder. This tube is heated by a Bunsen flame kept burning outside.

The modifications of this ignition tube, as used in his "Differential" and "Cycle" engines, have been pointed out above, in Chapter III. The *life* of an ignition tube depends on the material it is made of, and varies greatly according to the usage the tube receives. Thus life is shortened by intense heating, with sudden changes in pressure and temperature produced by the inrush of comparatively cool gases; whereas gradual changes tend to longevity. It is found that tubes deteriorate rapidly owing to high pressure within the cylinder at the moment of ignition. The thin tube, raised to white heat, is only exposed to the atmospheric pressure outside, hence the great pressure suddenly produced inside it by the explosion tends to burst the tube. On this account care must be taken not to overheat or soften the tube too much. Again, the fresh mixture of air and gas, when introduced, cools the inner surface of the tube. Moreover, it is necessary to use pretty thin tubes, since thick ones are not so easily raised by a flame outside to such a temperature that even poor gases may be readily ignited by contact with their inner surface.

The *average life of ignition tubes* in the Differential was 180 hours, and in the Cycle engine 120 hours. Here part of the mixture is *gradually* compressed into the tube under the most favourable conditions. The tube is constantly open to the cylinder, Fig. 34, page 51, and the length to the heated part of the tube is so adjusted that the small portion of the explosive mixture gradually forced into it becomes ignited and has just time to fire the main charge in the cylinder at the proper instant. It is evident the time of ignition in this way must vary with the speed of the engine.

However, the hot tube gives a good regular ignition, and with slight modifications is now being largely used in practice in the Atkinson, Otto, Stockport, and other compression engines. Ordinary wrought-iron gas tubing is not very expensive; and when a tube becomes choked up or burnt out, it can be easily removed. A certain alloy of silver, specially prepared, is found to last much longer than iron, and some other more suitable material may soon be discovered.

*Crossley's Hot-tube Ignition*:—With hot-tube ignition, unless when carefully timed, there is the possibility of premature and irregular explosions, causing danger and waste of gas. In order to get rid of these disadvantages and regulate the time of explosion, Messrs. Crossley employ an ignition valve which opens communication between the red-hot tube and the combustible mixture in the cylinder, only at the right time for the explosion.

The details of this arrangement for ignition are shown in Figs. 145 and 146. A piece of ordinary wrought-iron gas tubing, T, about $\frac{3}{8}$ or $\frac{1}{2}$ inch in diameter, is closed at the upper end and kept red hot by the flame of a Bunsen burner B, as well as by the asbestos lining R in the chimney.

The port C communicates directly with the interior of the engine cylinder at the charging end, receiving from it a rich mixture of gas and air. The passage between the hot ignition tube T and the cylinder is closed and opened at the right moment by the timing valve E, actuated by the lever L and a double cam on the side shaft of the engine.

During the compression stroke this ignition valve E is lifted by the lever L, the small end enters the hole D opposite it closes this elbow-shaped port, and so stops the passage of any flame to the cylinder. At this time any leakage of gas past the peg E, as well as any gases in the igniter tube T, escape freely to the atmosphere through the vent-hole or outlet A, so that there is no extra pressure in the tube T during compression in the cylinder.

FIG. 145.

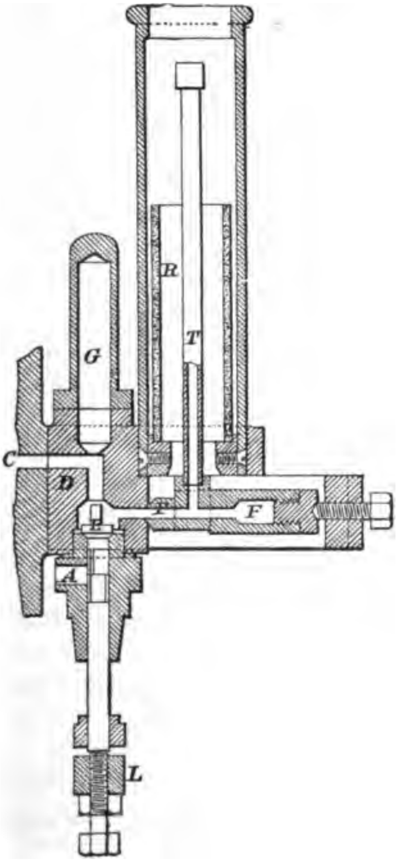
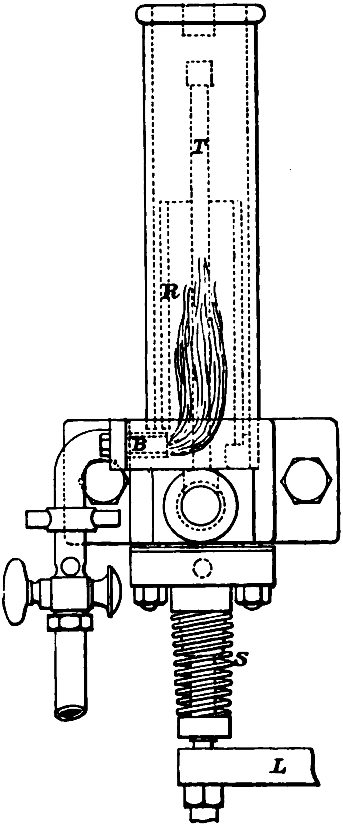


FIG. 146.



CROSSLEY HOT-TUBE IGNITER.

When ignition is desired the cam on the shaft ceases to hold up the lever L, compressing the spring S, and the valve

E is let drop on its seating, into the position shown in Fig. 145. Part of the rich compressed mixture from the cylinder rushes into and ascends the hot tube T, where it is ignited, and the flame being forced back into the cylinder, fires the whole charge.

The chambers G and F are expected to receive the burnt products from the passage C, so as to keep the portion of combustible mixture which enters and ascends the igniting tube T as pure and free from residuum as possible.

The loose tube-holder piece can be easily taken out by slackening back the set-screw at the end of F, the separation taking place at the mitre joint at P. Then the old tube can be removed and a fresh one screwed in.

The red-hot tube T becomes burnt in a peculiar fashion, and requires frequent renewal. The burning makes the metal swell, become distinctly granular in structure, and finally chokes up the tube. An igniter tube made of wrought iron lasts only about 30 hours.

This *short life* is due partly to the high temperature at which the tube is worked, but mainly to the action of the timing valve E, which causes a *sudden rush* of comparatively cool residuum along with part of the highly compressed charge into the red-hot tube T, and rapidly chills its inner surface.

Further, the timing valve E should be kept clean, and must fit its seat truly, so as to close the passage D properly, otherwise a slight leakage of compressed gas from C might cause premature ignition and waste.

*Stockport Igniting-tube:*—An ignition tube made of a certain alloy of silver, and specially prepared for the Stockport engine, is stated from experience to last *six months* under ordinary working conditions.

This tube bids fair to remove one great drawback to this mode of ignition. A chimney and hood are arranged around the tube, so as to regulate the draught and keep up a constant temperature in the tube, which tends to longevity.

Experience shows that hot-tube ignition is easily managed, even by ignorant attendants, and when accurately timed, makes the engines more reliable under all circumstances than with slide ignition valves carrying flame. At the same time, the heat of the tube cannot equal in intensity that of the electric spark or voltaic arc, which is near the temperature of volatilisation of the insulated points between which the arc passes. Hence the continuous stream of electric sparks, which is practically unaffected by ordinary currents of cold gas and air, affords the surest and most powerful means of igniting poor gaseous mixtures under high pressure in the cylinder of the internal combustion engine.

# CHAPTER VIII.

## ELEMENTARY PRINCIPLES AND CALCULATIONS.

THE reader is not expected to rest satisfied when he becomes familiar merely with the mechanical details and working of several gas and petroleum engines. He will best obtain a real grasp and thoroughly useful knowledge of this subject by adopting the natural method of study—that is, *by making trials, actual experiments, and measurements for himself.* The practical man can readily measure the work done by an engine for a given consumption of fuel; and at the same time he may take indicator diagrams to find out what is going on in the cylinder. In order to obtain the best conditions of working, he will naturally inquire into all the sources of waste, and how it comes that one engine is more efficient than another. Again, in the laboratory, *quantitative experiments* should also be carried out on *heat* and *work*, including the conversion of heat energy into mechanical energy to do useful work. The nature and laws of gases will be investigated, and experiments made to determine the *amount of heat generated by burning a cubic foot of different kinds of gas.*

The next step will be to *make use of the results obtained* in this way. The student will seek to derive useful information from the indicator diagram, and to clearly understand the meaning and cause of all its peculiarities; in a word, to find what it reveals to him regarding the working of the engine and the behaviour of the gases in the cylinder. He should also be able to MAKE CALCULATIONS and deduce practical conclusions from his own observations on the performance of heat engines.

In order to start with exact notions, we shall briefly consider some of the elementary principles and fundamental facts necessary for a clear conception of the theory and practical possibilities of the internal combustion engine.

All measurable quantities can be expressed in terms of the three fundamental units of *length*, *mass*, and *time*.

In Great Britain the standard of LENGTH is the YARD, defined by Act of Parliament as the distance between the centres of two gold plugs in a bronze bar, kept in the Standards Office of the Board of Trade, the bar being at the temperature 62° Fahr. The third part of the standard yard called one *foot* is the engineer's unit of length.

The unit of TIME is one mean solar SECOND.

The MASS of a body is the quantity of matter or stuff in it.

The British legal *unit of mass* is the mass of a certain piece of platinum, kept in the Standards Office, called *one pound* avoirdupois, and taken to represent 7000 grains.

FORCE *is that which moves or tends to move matter.* In *gravitation-measure*, forces are compared with the unit of *weight*, that is, the downward pull or attraction of the Earth on unit of mass at the sea-level at Greenwich. This is commonly called *the weight of one pound*, or more accurately the force of *a pound's weight*, and is the unit of force employed by engineers. But the downward pull of the earth on a given mass (as measured by a spring balance) depends upon their *relative position*, in fact, varies with the latitude and distance above the sea-level, according to Newton's *universal law of gravitation*, that the mutual attraction between two bodies is directly proportional to the product of their masses, and inversely as the square of their distance apart. Hence the gravitation unit of force, that is the weight of a body, will vary at different places on the Earth's surface, and another unit, independent of the Earth's attraction, has been selected for general reference.

One of the effects of a force, when applied to a given mass, is to accelerate its motion, and

$$\textit{force} = \textit{mass} \times \textit{acceleration}.$$

The British *absolute unit of force, a poundal, is that force which acting on the mass of a pound for one second, imparts to that mass a velocity of one foot per second.*

The acceleration of bodies falling freely by the attraction of the Earth is called the intensity of gravity, $g$, at the place. Experiment shows that $g$ is 32·088 at the equator, 32·18 at London, about 32·2 for Great Britain, and the weight of a body will vary accordingly, since

$$weight = mass \times gravity.$$

Hence $\quad$ 1 lb. = 32·2 poundals.

It may be convenient to remember that a GALLON* *of water weighs* 10 lb. at the standard temperature 62° F.; also one cubic foot of pure water at 4° C. weighs 62·4 lb. or about 1 000 oz.

The French standard of length is the MÈTRE, which is the length of a certain rod of platinum at 0° C. The hundredth part of this, called a CENTIMÈTRE, is the unit of length in the centimetre-gramme second system† recommended for scientific measurements by the British Association, and adopted by universal consent by the International Congress at Paris in 1881. One centimetre is equal to 0·3937 inch, or 1 inch = 2·54 centimetres. One metre is 100 centimetres or 39·37 inches. One cubic foot = 28·3153 litres, and 1 litre = 1000 cubic centimetres.

In the C. G. S. system a *gramme* represents the mass of a cubic centimetre of pure water at 4° C. and is equal to 15·432 grains. Thus 1 lb. = 453·59 grammes. A *kilogramme* is 1000 grammes or 2·2 lb.

The unit of force is a *dyne*, or *that force which, acting on a gramme for a second, generates a velocity of a centimetre per second;* that is, gives to it unit acceleration, according to the above law

$$F = a\,m,$$

where F stands for the force, $m$ the mass, and $a$ the acceleration. The pull of the Earth on a gramme, called a gramme's weight, is 981·17 dynes at London. A pound's weight is 444,971 dynes at

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* According to this Standard, the weight of a cubic inch of distilled water is 254·458 grains, at 62° F.; but measurements, by means of the standard yard and pound, prove that the weight of a cubic inch of pure water is 252·769 grains.

See Professor Everett's *Units and Physical Constants.*

London, 443,611 dynes at the equator, and would be 445,879 dynes at the pole.

A force is always distributed over some area, however small, and the *force exerted on unit area of surface is called the* PRESSURE. We shall take the pressure of one atmosphere as 14·73 lb. per square inch. The standard atmospheric pressure is that of 29·905 inches of mercury at the sea-level in the latitude of London.

In the C. G. S. system the atmospheric pressure is 1,013,800 dynes per square centimetre in London. The standard pressure corresponds to 760 millimetres of mercury at 0° C. in north latitude 45°. All ambiguity due to the variation of gravity could be avoided by adopting a pressure of *one megadyne per square centimetre* as the standard atmospheric pressure. This standard is equivalent to 749·64 mm. or 29·514 inches of mercury at 0° C., or nearly 14·5 lb. per square inch, at the sea-level at Greenwich.

## WORK.

*Work* is done when a force is exerted through any distance in its own direction. *The measure of a force in pounds, multiplied by the distance in feet through which it acts, gives the work done by the force in foot-pounds.* The unit of work usually employed by British engineers is the work done by gravity on the mass of one pound in falling through a height of one foot, and is called *one foot-pound.* It is the amount of work necessary to raise a pound's weight one foot high, that is, to overcome the mutual attraction between 1 lb. and the Earth through a distance of one foot. If we raise 14 lb. a height of 5 feet against gravity, we do 14 × 5, or 70 foot-pounds of work, whilst this mass in falling through the same difference of level is capable of doing the same amount of work. In lifting a mass vertically we overcome the mutual attraction between that mass and the Earth, and do work; but in moving a mass in a horizontal direction there is no work done against gravity, we merely overcome the resistance of friction, and the work done is always found by multiplying the resistance by the distance through which it is overcome.

In a gas engine cylinder, the pressure of gas on the piston does no work until it moves the piston. If by heating the gas we keep its pressure constantly 60 lb. per square inch, whilst it expands, driving the piston through a distance of 200 feet; the piston exposed to the pressure having diameter 6 inches, how much work is done by the gas?

Answer:—The area of piston exposed to pressure is $0{\cdot}7854 \times 6 \times 6$ square inches; there is, therefore, a total pressure of $0{\cdot}7854 \times 6 \times 6 \times 60$ lb. on the piston, driving it through a distance of 200 feet.

Hence the work done by the gas on piston is

$$\text{force} \times \text{distance, or } 0{\cdot}7854 \times 6 \times 6 \times 60 \times 200,$$
$$\text{that is, } 339{,}292{\cdot}8 \text{ ft. lb.}$$

In general if $a$ square inches be the effective area of a piston exposed to a constant gaseous pressure of $p$ lb. per square inch, or a total force of $p\,a$ lb., which drives it through $l$ feet length of cylinder, then the amount of work done by the gas on the piston is $p\,a\,l$ ft. lb., and is independent of the time in which it is performed.

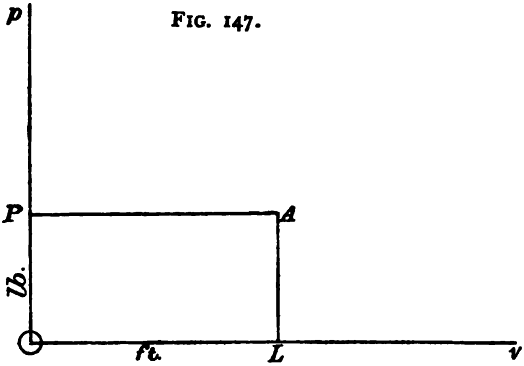
The British absolute unit of work, a *foot-poundal*, is the work done by a force of 1 poundal in working through one foot. The C. G. S. unit of work is an *erg*, which is the work done by a *dyne* in working through a centimetre. The gramme-centimetre, another unit of work, is the work done in raising a mass of one gramme against gravity through one centimetre, and is equal to 981 ergs. The unit of work generally employed by French engineers is the kilogramme-metre, that is, the work done in raising a kilog. against gravity through a height of 1 metre. It is equivalent to 98,100,000 ergs. A convenient *practical* unit of work is the *joule*.

1 JOULE = 10,000,000 ERGS.

**Work can be represented graphically by an area.** This is obvious in the case when the pressure is constant throughout the travel of the piston.

Take a height O P, Fig. 147, to represent the total pressure or force $p\,a$ *pounds*, to some suitable scale, and at right angles to it, draw O L to represent the length $l$ in *feet* travelled by a piston under this constant pressure, then the rectangular area O P A L represents the work done $p\,a\,l$ in *foot-pounds*, since it is found by multiplying the value of O P by that of O L.

FIG. 147.

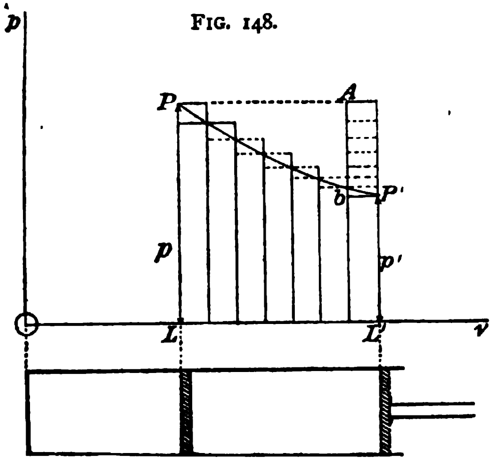


To prove that this holds true when the pressure is variable. Let distances measured from O along O$p$ or heights above O $v$ represent pressures in pounds per square inch, and distances along O $v$ represent lengths of cylinder swept out by the piston.

Suppose a mixture of gas and air enclosed in the cylinder, Fig. 148, its volume is given by the length O L of cylinder occupied, since it is equal to O L multiplied by the sectional area of cylinder, whilst its pressure of $p$ lb. per square inch is shown by the height L P. Thus the *point* P *represents the condition of the mixture as regards pressure and volume* by the height above O $v$, and distance from O $p$. It is evident that if either of these vary, the point P will change its position accordingly to indicate the corresponding pressure and volume, and the *curve traced out by the point* P will, moreover, be *a graphic representation of the law connecting the pressure and volume of the substance in the cylinder*, since it shows how the one varies with the other.

As the mixture of gas and air burns and expands, forcing the piston along the cylinder from L to L′, the pressure falls to L′ P′ or $p'$ lb. per square inch, as indicated by the curve P P′. If the area of the piston exposed to pressure be $a$ square inches, then the total effective pressure at L is $p\,a$ lb., and at L′ it has become $p'\,a$ lb. Divide the line L L′ into any number of equal parts, and construct the little rectangles as in Fig. 148.

FIG. 148.



Now conceive the pressure instead of falling gradually, as it really does, to remain constant during each short interval or motion of piston, and to fall suddenly by steps; then the area of each rectangular strip would represent the work done, on every square inch of piston, by the gas during that part of the piston's motion, being equal to the average height or pressure multiplied by the distance this has moved the piston. In this way the sum of all the elementary rectangles would represent the total work done per square inch of piston, those above the curve being too great, and the others below it too small.

By dividing the distance, L L′, travelled by piston into a very great number of equal parts, and constructing rectangles on them, the heights will change less suddenly and approximate more closely to the real pressures; and when we imagine an indefinitely great number of equal parts in the line L L′, the pressures will fall gradually along the curve P P′. Now, by projecting across, as in Fig. 148, we see that the difference in area betwen the sum of all the longer rectangles extending above the curve, and the parts of them below it, is equal to the rectangle P′ A, having height equal to the difference of the pressures at P and P′, whilst its base P′ *b* can be made as small as we please by increasing the number of parts in L L′. The rectangle P′ A can thus be made smaller than any finite number. Hence in the limit, when L L′ is divided into an indefinitely great number of equal parts, the sum of all the rectangles below the curve becomes equal to the area of all those reaching above it; or, in other words, the sum of all the elementary rectangles equals the area L P P′ L′. Therefore, *this area, bounded by the curve* P P′, *represents exactly the work done on the piston by the burning gas in expanding from* L *to* L′.

It follows that the work done by a gas can be calculated when the law of its expansion is known.

If the sectional area $a$ be expressed in square feet, then $a\,l$ cubic feet is the small change in volume ($dv$ say) of the gas, whilst the pressure remains $p$; therefore the element of work done ($dw$), in that short interval, is $p\,a\,l$ equal to $p\,dv$. This may be represented by the area of one little strip, Fig. 148. Adding together all the little strips between the two limits of volume $v_1$ and $v_2$, that is, adding up all the values of $p\,dv$ between these limits, we get

$$\int_{v_1}^{v_2} p\,dv = \int_{v_1}^{v_2} dw = \text{W},$$

where W stands for the work done by the gas in expanding from volume $v_1$ to volume $v_2$.

Suppose the law, $\frac{p\,v}{\text{T}} = \text{R}$, that is, $p = \frac{\text{R}\,\text{T}}{v}$, holds for the gas during the expansion; then, we have

$$\text{Work done} = \int_{v_1}^{v_2} p\,dv = \int_{v_1}^{v_2} \frac{\text{R}\,\text{T}}{v}\,dv = \text{R}\,\text{T}\int_{v_1}^{v_2} \frac{dv}{v},$$

and

$$\text{W} = \text{R}\,\text{T}\log_e \frac{v_2}{v_1} = p\,v\log_e \frac{v_2}{v_1}.$$

## WATT'S INDICATOR.

WATT'S INDICATOR enables us, by this graphic method, to trace all the alterations in pressure and volume of the working substance in the cylinder of an engine, and to calculate the work done by the steam or gas on the piston.

The original object of the indicator was merely to register the pressure in the cylinder of a steam engine at every point throughout the piston's stroke. This instrument, however, revealed to its inventor—Watt—much more about the working of his engines. From its diagram of what was going on in the cylinder, and the behaviour of the steam therein, he could see at a glance whether the valves, steam ports, and piston were working properly, and he was enabled to improve them accordingly.

Watt's indicator consists of a small cylinder screwed into a hole tapped near one end of the engine cylinder so that the steam can have free access to it. A closely-fitting piston works in this little cylinder with a piston-rod, carrying a pencil directly attached at its upper end clear of the cylinder. Above the piston is a spiral spring, which keeps it down until the steam pressure from the engine cylinder acting on its lower side overcomes the atmospheric pressure on its upper side, compresses the spring, and forces the piston with piston-rod and pencil upward. The amount of compression or extension of the spring through a given range is proportional to the force applied, and each spring is tested before being used in the indicator, so that the pressure in the cylinder above or below that of the atmosphere is shown by the rise or fall of the pencil fixed on the piston-rod. If the pressure underneath be equal to that of the atmosphere, the piston does not move, if it be greater, the piston is driven upwards and the spring compressed, but when the pressure is less than atmospheric, the elasticity of the spring extends it, and causes the piston to descend. The pencil traces a line on a piece of paper attached to a plain smooth board, which is placed upright and made to move to and fro by a suspended weight in exactly the same time as the engine piston, only through a shorter range. A horizontal line will be traced when the pressure in the engine cylinder remains constant, and a gradual rise or fall in the pressure will be indicated by a curved line.

In Watt's slow speed engines small changes in the very low pressures employed could be shown by a long spring, but a *sudden* change of pressure would give a *vertical* line followed by vibrations of the spring, kept up by the inertia of the indicator piston and moving parts, which would carry the pencil beyond the true position for that pressure, and cause it to trace an irregular wavy line, not an accurate representation of the pressure.

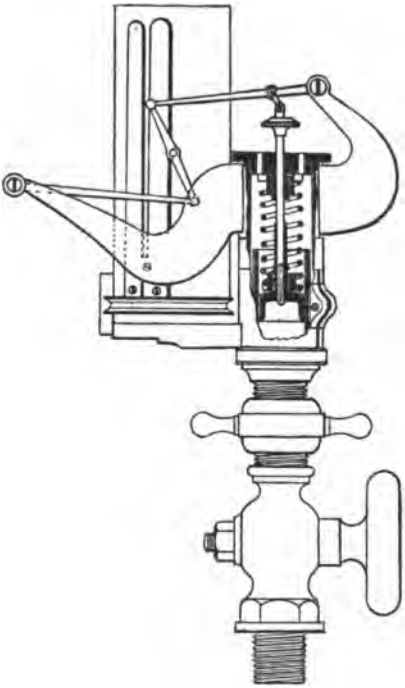
Higher pressures and quick speeds of piston increased this difficulty and necessitated improvements in the indicator. Since Watt's time, MCNAUGHT replaced the board carrying the sheet of paper by a hollow cylinder with the paper wrapped round it. This paper-covered drum was free to rotate about a vertical axis when pulled by a cord attached by reducing gear to the piston or directly to some reciprocating part of the engine; and there was a flat spring coiled inside to bring it back to its original position, as did the suspended weight in Watt's indicator. This was more compact, but retained the weak points and main defects of the old form, a long spring being used, and the pencil carried by an arm *directly* fixed on the piston-rod.

The RICHARDS INDICATOR, designed in 1862 by Mr. Charles B. Richards, of Hartford, Conn., marks a great advance by the use of *light piston and moving parts*, with a *short, stiff spring*, allowing the indicator piston only a *short range of motion and magnifying this* by an arrangement of levers like Watt's parallel motion.

One form of this indicator is given in Fig. 149, with the light piston and spiral spring in section, as made by Messrs. Schäffer and Budenberg, of Manchester. (Compare Figs. 151 and 157.)

A modified form of this instrument, as made by Messrs. Elliott Brothers, of London, is also shown in Fig. 150, with screw driver, indicator spring, and cleaner.

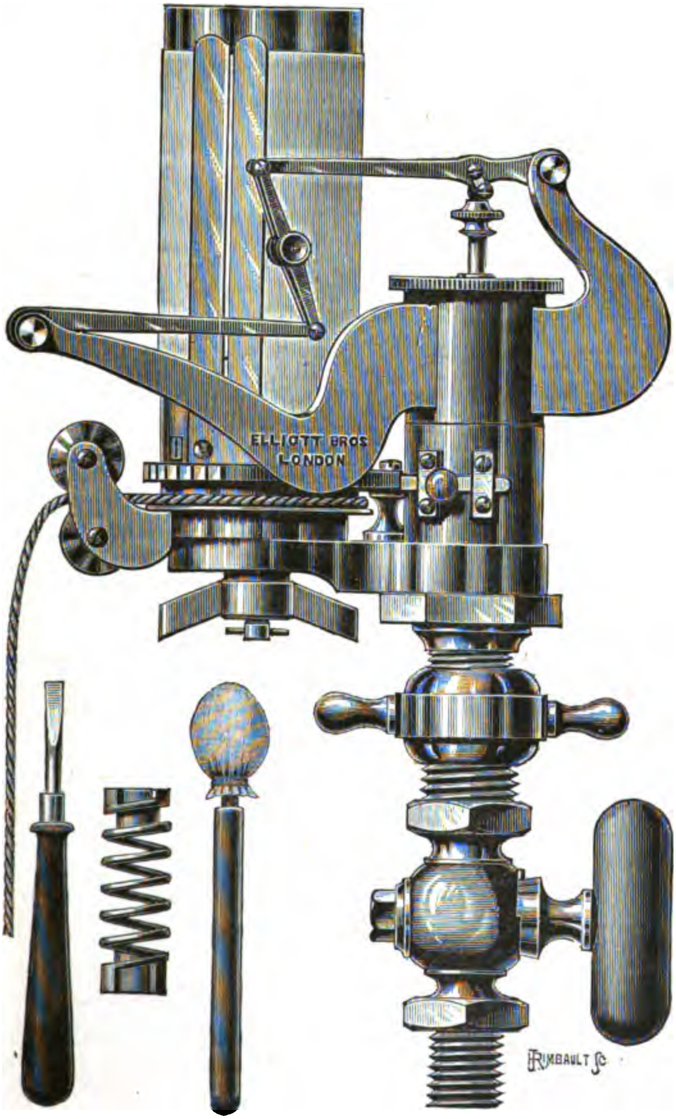
FIG. 149.



RICHARDS' INDICATOR.

The lower part is to be screwed into a hole drilled in the side of the engine cylinder near its end and over the clearance space untraversed by the piston. Sometimes the two ends of a steam engine cylinder are connected by a pipe, with a three-way cock, to which the indicator may be attached. The indications of the steam pressure at both ends of the cylinder can be obtained in rapid succession by simply turning this cock one way or the other. However, long narrow pipes

FIG. 150.



THE RICHARDS INDICATOR.

must not be used between the cylinder and indicator; on the contrary, the passages must be wide and short, so as not to throttle the steam or gases, thereby reducing the pressure.

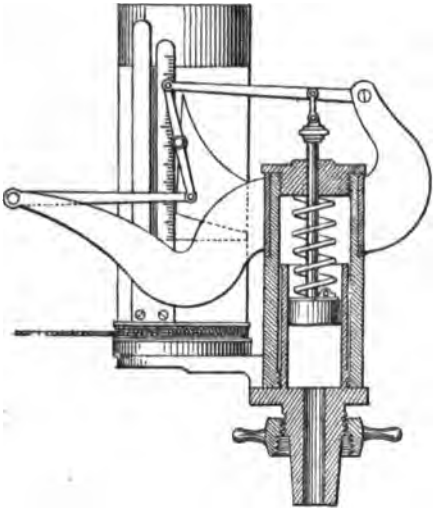
The little cylinder of the indicator, Figs. 149 and 151, contains a true and easy fitting piston, the space below which must be in perfectly free communication with the engine cylinder when the stop-cock is open. In the upper part of this cylinder there is a short spiral spring, shown detached in Fig. 150, one end of which is attached to the little piston and the other end is screwed into the top cover. This is always open at the top to the atmosphere. When the indicator cock is opened the piston is exposed to the same gaseous pressure as the piston in the engine cylinder, and is urged upwards against the spiral spring. The compression or extension of this spring is proportional to the pressure above or below that of the atmosphere, as in Watt's indicator.

The motion of the indicator piston is magnified and registered by a pencil moved from the piston-rod by the combination of two levers, which are equal in length, and connected by a link, forming Watt's parallel motion. Since the movable ends of these two arms describe equal arcs from opposite centres, the pencil carried by the connecting link midway between them will evidently not follow either, but trace out an approximate straight line.

The piston-rod is attached to one arm at one-fourth its length from the fulcrum. Hence any movement of the piston is magnified four times at the end of the lever, or by the pencil, which has the same range. The stout curved arm carrying the parallel motion turns freely around the cylinder on a collar, to allow the pencil to mark the paper on the drum when desired. The pencil is generally made of metal, and marks a piece of specially prepared metallic paper, called an *indicator card,* which is fixed on the drum. To avoid the friction of the metal point some engineers use a hard lead pencil and glazed paper.

The cord in the groove round the bottom of the drum can be attached to some part having the same reciprocating motion as the motor piston of the engine, only within a shorter range. Usually a temporary piece of reducing gear is attached to the piston, and a cord joins it to the paper drum to obtain an accurate reduction of the piston's motion. This cord is selected of the most suitable quality, strong, but not stiff or heavy. Sometimes it is replaced by a thin steel wire so as not to be stretched by a slight variation in the pull of the spring or reducing gear. The cord pulls the paper drum and makes it rotate in opposition to a coiled, flat spring inside it, which always keeps the cord tight and brings back the drum to its original position.

FIG. 151.



THE RICHARDS INDICATOR.

The drum can be stopped or started at any time without disconnecting the cord which moves it. This is done by the device known as DARKE'S PATENT DETENT, provided with this indicator as in Fig. 150, and described below at page 252.

The holder of the little pulleys which guide the string is adjusted by the fly-nut under the drum, so that the cord runs freely straight off.

Attention to such details is always necessary, inasmuch as it is of the greatest importance to make the *paper-drum move to and fro freely under the pencil in exactly the same time and way as the piston travels backward and forward in the engine cylinder.* The cord is adjusted to give a sufficiently wide range of motion to the drum, but the pencil must not be allowed to knock against the clips that hold the paper, else the whole travel of the piston will not be indicated.

In order that the pencil may indicate with delicacy, *slight variations* in pressure, simultaneously as they occur in the engine-cylinder, that is to make the instrument at once sensitive and dead beat, it is necessary to have a comparatively short and delicate spring, a light indicator-piston, having a large area exposed to the pressure, and very light moving parts attached thereto, suited to ordinary work, and giving minimum friction at the rubbing surfaces. It is difficult to realise all these conditions at the same time in practice, without vibrations.

Indicator-springs of different strengths are made to fit the same instrument, and selected according to the nature of the pressures to be measured. Their indications give the pressure in pounds per square inch as measured by an accurately graduated scale supplied with each spring. The spring ought to be frequently tested in the indicator by applying pressure of steam, or hot air, to the piston in exactly the same way as it is intended to be used, because springs yield 2½ or 3 per cent. more when hot than cold. When a spring is disturbed by pressure suddenly applied, it vibrates, causing the pencil to jump up and down, thus tracing a wavy line instead of a regular curve. This jerky unsteady motion is very inconvenient. Mr. Richards partly overcomes the difficulty by employing short strong springs, and magnifying their motion.

For slow-speed steam engines below 150 revolutions per minute, the vibrations of the indicator-spring are in this way very much reduced, but we cannot expect to get rid of them altogether. They may, however, be eliminated in any case where the effect to be measured follows a regular law, as in the case of the expansion part of an indicator diagram. The rule* is as follows:—Draw two curves, A and B, one touching all the crests or highest points of the wavy curve, and the other touching all the lowest points; draw a number of ordinates cutting these curves. The points of bisection of the parts intercepted between A and B, lie on the correct curve.

Richards' indicator is suitable for the pressures and speeds common to the steam engine at the time it was introduced, and it has been of great service to the engineer, enabling him to improve and perfect that prime motor. But with still higher speeds, and rapidly varying pressures, the parallel motion mechanism which carries the pencil, gets up momentum, and is violently shaken, damaging loose joints, and giving inaccurate indications of the real pressure in the cylinder.

Thus an indicator, well adapted to the ordinary steam engine, may be quite unfit for use on the gas-engine cylinder, and may soon come to grief if subjected to the sudden pressure of an explosion, acting like a sharp blow. The pencil arm is liable to get bent or broken. In fact the Richards indicator is not well suited for gas-engine work, which severely tests the very best indicators. However, the improved Richards, is sometimes used on the gas engine.

THOMPSON'S INDICATOR.—The next indicator, both in order of time and perfection, is that introduced by Mr. J. W. Thompson, and seen in half sectional elevation, Fig. 152, as made by Messrs. Schäffer and Budenberg. The chief feature here is the novel arrangement of light levers carrying the pencil.

The link connecting the pencil-arm to the piston-rod has a ball and socket joint at the lower end to allow free motion. A movable collar around the upper part of the cylinder, swings round against a stop to prevent undue pressure of the pencil on the paper. This collar carries a fixed standard with radius bar, as well as a link with the fulcrum of pencil-arm at its upper end; the lengths of these levers are so proportioned as to give the pencil an approximate straight line motion.

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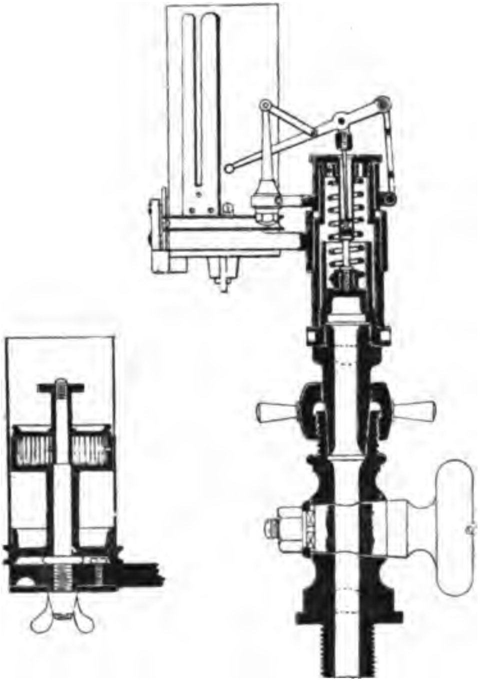
* See communication by Professors Ayrton and Perry to the *Journal of Soc. Tel. Eng.*, p. 139, vol. v., 1876.

The parts which move with a high velocity are made as light as possible, consistent with strength and stiffness, in order to reduce their inertia to a minimum. This calls for the greatest nicety of workmanship.

FIG. 152.



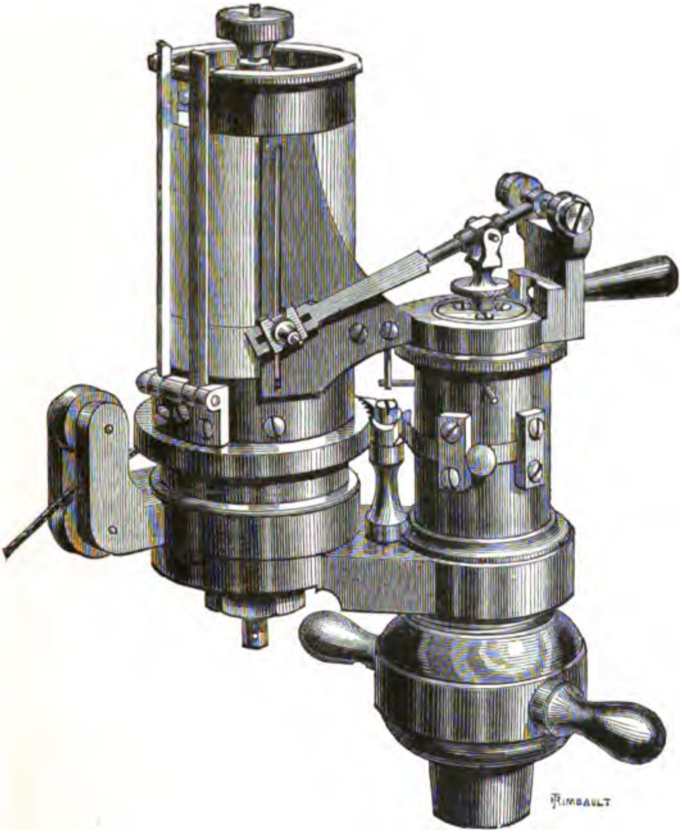
THOMPSON'S INDICATOR.

In the older forms of instruments, the cock and inlet passage were usually $\frac{5}{16}$ inch in diameter; but to give free admission and prevent any loss of pressure between the engine cylinder and that of the indicator, the bore is $\frac{1}{2}$ inch in the Thompson indicator.

The *paper drum* is given separately in section, Fig. 152. By removing the outer cylinder, loosening the nut on the top of the drum spindle, and by turning the disk holding the flat spring inside, the latter may be readily adjusted to suit any speed of engine up to 450 or 500 strokes per minute. The *spiral springs* are graduated for a range of pressures from 6 lb. up to 375 lb. per square inch.

Darke's high-speed indicator is a neat little instrument, Fig. 153, made by Messrs. Elliott and suitable for gas-engine indications. It is specially designed for high-speed steam engines, and has very light moving parts, their total weight being about 1¼ ounce.

Fig. 153.



Darke's Indicator (¾ Full Size).

The piston-rod is made hollow and the springs short.

Instead of the old heavy parallel motion mechanism, the pencil arm is a single lever pivoted by centre points on the two ends of a T-shaped head, and connected to a jaw on the piston-rod head by a sleeve free to slide through a short range. The centre of gravity of the lever and pencil cross-head is almost directly over the piston-rod centre. The free end of the lever carries a loose sliding piece, with a holder for the metallic pencil. The length of the lever is 2 inches, and the movement of the pencil four times that of the piston. The pencil is kept in a vertical straight line by a slot guide in a plate, which is fixed to the collar on the cylinder top, and is moved round along with the pencil arm by a handle, to make the pencil touch the paper on the drum when a diagram is to be taken. The drum is made to hold a continuous roll of diagram paper, which comes out by a slit and is wrapped round the drum and held by a clip. Each card, when taken, is torn off, and part of the paper roll pulled out and fixed round the drum as before.

The drum can be stopped while the engine is running without disconnecting the cord, by means of *Darke's patent detent.* This consists of a tooth or pawl, which gears into the teeth of the ratchet segment at the lower part of the paper drum, and stops it by the action of the flat spring attached to the cylinder when the little knob is moved in one direction. When the knob is moved in the opposite direction the drum is released by this flat spring throwing the pawl out of gear with the ratchet teeth. This arrangement is very convenient when several diagrams are to be taken in rapid succession from an engine running at high speed.

It is found that there are **four principal causes of error in indicators**, which affect the diagram :—

1. The *inertia of the piston and parallel motion mechanism* attached thereto. The effect of this is to increase the size of the diagram, and alter its shape. The obvious remedy is to *reduce the weight* of the piston, piston-rod, and other moving parts, as far as strength and stiffness will allow. On this account the use of the metal aluminium, or *aluminium bronze*,

which is harder and stronger, would improve the instrument very considerably.

2. The *inaccuracy of the indicator-springs.* — Ordinary spiral-springs give different results, depending on *how* the load is applied; hence they ought always to be tested, and rated in the indicator *under exactly the same conditions as in practice*, both as regards *temperature*, and the *application* of the pressure.

3. The *friction* of the pencil on the paper keeps the pencil behind its true position, hence the necessity for *careful manipulation.* A graphite or hard lead pencil may be used, and a stop with screw-adjustment provided to prevent the pencil being unduly pressed against the paper. The paper-drum spindle, and every part of the instrument, should be kept properly lubricated to diminish friction. Also, to ensure perfect freedom in the action of the indicator-piston, it should be an easy fit, with no possibility of sticking whilst the hot working-fluid has free access around it.

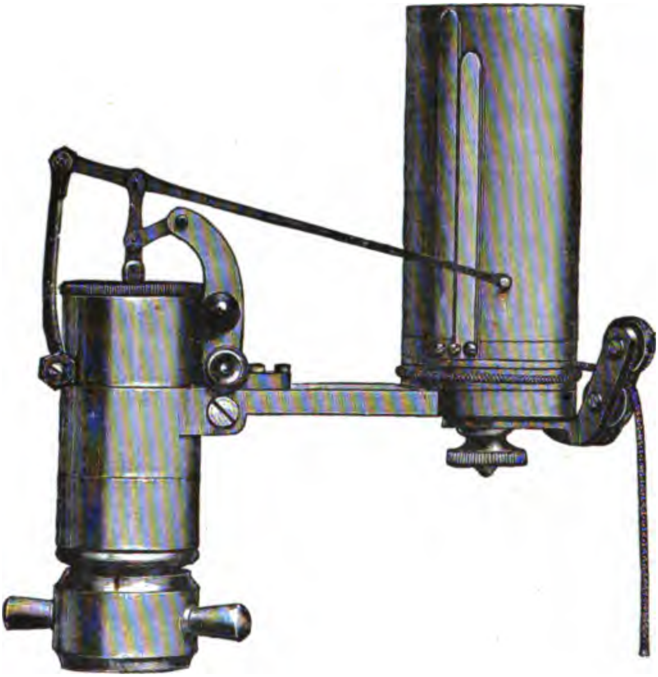
4. The *unequal stretching* of the indicator-cord, due to the varying tension in it necessary to overcome the friction and inertia of the paper drum, as well as to the resistance of the drum-spring during the forward and backward travel of the engine-piston. Consequently, the diagram will be still further distorted, and the mean indicated pressure diminished. To avoid this, the stress on the cord should be uniform throughout the travel of the engine-piston by making the resistances it has to overcome as nearly constant as possible. The cord must not be too long, and a new one should be well stretched before being applied to the indicator. Sometimes thin steel wire is used with a view to get rid of this source of error.

The CROSBY INDICATOR, shown in Figs. 154 and 155, as made by the Crosby Steam Gage and Valve Company of Boston, U. S., is coming into general use, and is admirably adapted to overcome the difficulties connected with modern high speeds, as well as suddenly varying pressures, such as are common in the best engines. It simply, but effectually, meets the weak points above referred to.

It has a very light piston, parallel motion and drum.

The spring, Fig 156., is made of one piece of steel wire, wound from the middle into a double spiral, its ends being screwed into the wings of the heavy spring-head D, fixed to the cylinder-cap A, Fig. 155.

FIG. 154.



THE CROSBY INDICATOR.

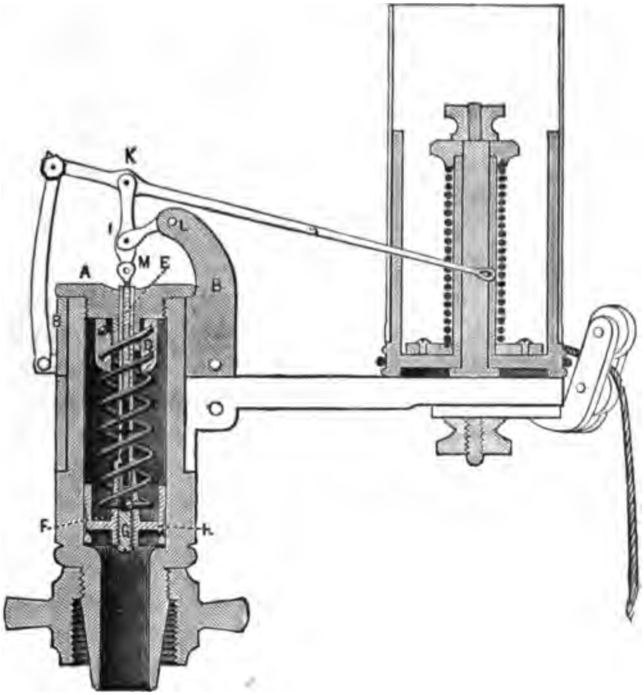
The final adjustment of the springs is made by simply screwing the ends in or out of the head D. On the middle of the spring is brazed a small steel ball which fits a socket in the hollow piston-rod, and is adjusted to the proper tightness by the screw G, so as to allow free motion, and prevent sticking or twisting, the thrust on the spring producing a perfectly axial compression.

The steam or gas from the engine passes into the chambers

F and H, around the piston, and keeps it from touching the sides of the cylinder.

Besides having the bearing in the centre of the piston by the ball and socket joint, there is the further material advantage of reduction in weight at the lower end of the spring where it is most needed, because this part has the same motion as the piston, and therefore would otherwise have great inertia.

Fig. 155.

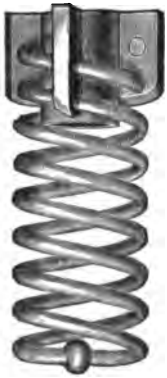


The Crosby Indicator.

The springs are rated in the indicator by the pressure of dry hot steam, so as to be accurate when in actual use. It is desirable not to have the diagram more than 1·75 inches high, hence, when measuring high pressures, use stiff piston-springs, which will at the same time lessen vibrations.

The very slight movement of the indicator spring is then magnified to 6 times the range by the pencil. The long pencil-arm, necessary for this multiplication, is the weak part of the instrument. For gas engine purposes, it is advisable to have the pencil arm made of L-shaped section steel, tapering towards the point carrying the pencil, so as to have its centre of gravity directly over the piston-rod centre, and especially to be stiff and strong enough to withstand sudden and frequent blows delivered on the indicator piston from the explosions in the cylinder of the internal combustion engine.

FIG. 156.



CROSBY SPRING.

With many indicators, in careless hands, the friction of the pencil on the paper sometimes amounts to tearing of the paper or bending of the pencil when it is pressed too hard against the paper. This is prevented in the Crosby by a stop for the sleeve on the cylinder Fig. 154, carrying the pencil movement. A screw comes against the stop and can be adjusted to a nicety, so that the pencil point is allowed just to touch the paper and make a visible mark.

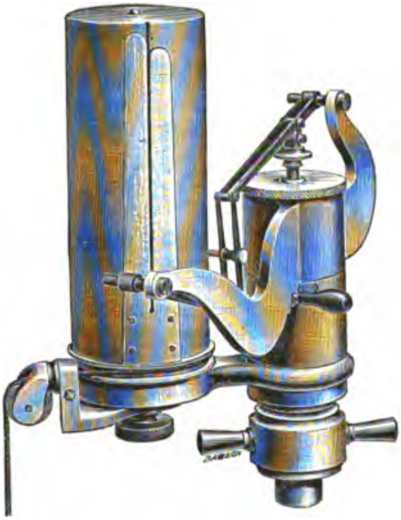
The paper-drum has a *short spiral spring* which can be tightened and adjusted by the collar and locknut at the top to suit the speed of the engine to be indicated. This spring offers increasing resistance as it is compressed by the rotation of the drum, overcomes the inertia and fricton of the drum, and thus maintains a constant stress on the cord connected by the reducing-gear to the engine-piston. Special tests show that the stress on a cord attached to a Crosby drum making 450 revolutions, is fairly uniform throughout the travel of the piston.

At the bottom of the paper-drum there is a swivel guide-pulley, which can be turned and clamped in such a position that the cord runs straight and directly from the drum motion to the reducing gear.

When used in a careful manner by practical and intelligent engineers, the Crosby indicator gives good and reliable cards.

The Crosby Company also make, at a small cost, an improved and substantial form of the Richards' indicator, Fig. 157, for ordinary work. The chief modifications are:—

FIG. 157.



RICHARDS' INDICATOR.

1. The use of a *spiral spring* instead of the flat clock spring in the paper-drum.

2. The method of making and finally adjusting the indicator spring, under hot steam, to the proper scale strength, by screwing the spring further in or out of the heavy head.

3. The screw and stop adjustment of the mechanism carrying the pencil and parallel motion, to prevent knocking or pressing of the pencil too hard against the drum.

4. The swivel guide pulley to run the cord straight from the drum.

## HOW TO TAKE AN INDICATOR DIAGRAM.

We are now in a position to understand HOW TO USE THE INDICATOR to take an indicator diagram from the cylinder of an internal combustion engine.

Suppose, for instance, we have an Otto Engine as modified by Crossley.

First screw the indicator into the hole drilled for it near the end of the engine cylinder over the clearance space.

Attach the cord to the reducing gear on the engine piston, and adjust the length of the cord so that the drum does not strike the stops at either end of its motion, and yet have as long a range as possible. Wrap a sheet of paper closely on the drum, and draw its ends tightly round the clips.

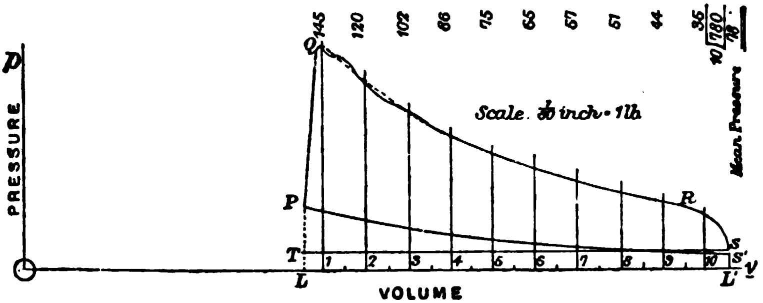
Next, adjust the screw of the pencil movement against the stop, so that the pencil only just touches the paper, and the pressure is enough to make a distinctly visible but not heavy mark on the paper. This precaution saves the fine pencil point, and prevents excessive friction that would cause errors in the diagram.

Open the indicator-cock, and the pressure of the gas from the engine cylinder forces the indicator-piston up against the spiral spring or allows the latter to press it down, thus causing the pencil to play up and down. This warms the instrument, indicates the highest and lowest pressures we may expect, and thus affords a guide to the proper strength or scale of spring to select. If the cord be attached, giving the paper-drum the to-and-fro motion identical with the piston's at the same time that the cock is open, and the pressure of the stuff in the cylinder allowed to act on the indicator-piston, the pencil plays up and down. Now, by the handle on the sleeve carrying the parallel motion, bring the pencil round and press it very gently against the paper during one explosion and complete cycle of the engine. Then remove it, and we have a closed curve like P Q R S T S′ P, Fig. 158.

This is called an *indicator diagram.*

When the indicator-cock is closed the indicator-pencil remains at rest, but as the paper-covered drum is moved underneath it, a horizontal line is traced out. This is called the *atmospheric line*, since it represents the atmospheric pressure on the indicator-piston, and its length is the travel of the piston in miniature. Detach the cord or move the detent spring to make the pawl go into gear with the ratchet teeth, and hold the drum at rest against the coiled spring inside it.

FIG. 158.



INDICATOR DIAGRAM (*Half Size*).

Take the card off the paper drum and replace it by a fresh one.

While this is being done, the number of explosions and revolutions per minute should be counted, and marked on the indicator card, with the scale of the spring used, the diameter of engine cylinder, and length of stroke. It is also important, and convenient for reference, to note on a corner of the card the date and number of the diagram if one of a series from any particular engine.

It will be observed that the indicator diagram is the result of two motions: the *vertical motion* of the pencil due to the pressure in the engine cylinder, and the *horizontal motion* of the paper which represents the *travel* of the motor piston. Hence any point on the curve indicates the *pressure* in the cylinder corresponding to that position of the piston given by the horizontal distance along the atmospheric line.

The strength of the spring in the indicator has been carefully tested beforehand, and the scale is marked on the diagram, so that by measuring the vertical distance of any point on the curve above or below the atmospheric line, with this scale, we have the pressure, in pounds per square inch, of the working agent in the cylinder on the piston at every point throughout its stroke.

If the average height of an indicator diagram is 0·5 inch, and the scale is $\frac{1}{32}$, which means that a pressure of 1 lb. per square inch on the indicator-spring will produce a compression of $\frac{1}{32}$ inch, then the mean or average pressure is $0·5 \times 32 = 16$ lb. per square inch.

Measure a distance below the atmospheric line equal to 14·73 lb. per square inch on our scale and the line O $v$ drawn through this point, parallel to the atmospheric line, is the line of no pressures or the *vacuum line.* Heights above this represent *absolute* pressures.

## THE INDICATOR DIAGRAM.

Now *what does this indicator diagram tell us* about the operations in the Otto Gas Engine? During what is called *a complete cycle* of operations the working substance, in the cylinder, undergoes a series of changes in volume and pressure, and is brought back exactly to its initial state, whilst the indicator-pencil has been tracing this *closed curve.* We must bear in mind that, in the engine from which the diagram, Fig. 158, was taken, one end of the cylinder is open, exposing one side of the piston continually to the pressure of the atmosphere. The various pressures exerted by the gas in the cylinder, on the other side of the piston, in pounds per square inch of its area, are given by the diagram, and can be measured on it by the indicator-scale.

It will be most convenient to *find first the effective work done on unit area of the piston,* and this multiplied by the area of the piston exposed, will be the total work done on it by the gas during a complete cycle.

Let O $v$ be the vacuum line; heights above this represent absolute pressures, in pounds per square inch, whilst distances along it, measured from O, represent lengths of cylinder in feet occupied by the gases. When the piston is at the end of its stroke, O L is the length of cylinder having volume equal to the clearance-space including passages, and is about two-thirds of L L′, the travel of the piston. This is measured independently as well as L L′, which is twice the length of the crank.

Suppose now, to start with, the indicator pencil is at T, and L T represents a pressure of 14·73 lb., that is the atmospheric. As the piston moves from L to L′ the charge is drawn in, and the connecting cord pulls round the paper-drum underneath the pencil which marks the line T S′. The pencil scarcely moves, as the pressure is nearly atmospheric on both sides of the piston, and therefore no appreciable work is done. The gas and air inlet ports of the cylinder are now closed, and in the return stroke the piston compresses the charge; whilst the spring in the paper drum pulls it back, and the pencil rises with the pressure along the curve S′ P.

Here the work done by the piston on the working substance is shown by the area L′ S′ P L. During this back stroke the piston has been assisted in compressing the charge by pressure of the air on its other side, and L′ S′ T L is the work done on the piston. The difference S′ P T is the work done *by* the piston itself *on* the gases.

At P the charge is fired, and the pressure suddenly rises to Q, the burning gases expand, driving forward the piston, and the connecting cord again pulls round the paper-covered drum. The sudden rise in pressure to Q causes a tremor in the spring, which we have corrected by the dotted line Q R.

When the pencil is at R, the exhaust valve opens and the pressure falls more quickly. Still the gas is doing work on the piston to the end of the stroke at S. The pressure of the atmosphere on the other side of the piston has been a retarding force, which was overcome, and the work done *by* the gases *on* the piston is represented by the area T P Q R S.

During the back-stroke the exhaust-valve is open along S T, and the piston does work expelling the products of combustion, but is assisted by the atmospheric pressure on its other side, so we can only give the piston credit for the work represented by the very small area S S′ T bounded by the lines S T and T S′, which are nearly coincident.

The pencil is back again at T, and the products of combustion occupy the clearance-space, O L, just as when we started.

Neglecting for the moment the very small area S S′ T, we see that the area T P Q R S expresses the work done by the burning gases in moving the piston, and T P S′ is the work done by the piston in compressing the charge; therefore *the area* P Q R S *represents the effective work done on the piston, per square inch of its area, by the burning gases in the cylinder during one explosion or a complete cycle of the engine.*

Hence the area of the indicator diagram, or its mean breadth multiplied by its length, represents $p\ l$ ft.-lb. of *work done* by the gases in the cylinder on the piston, i. e. *the mean effective pressure in the cylinder, $p$ lb. per square inch, multiplied by $l$ feet, the travel of the piston or twice the length of the crank.*

From this it is evident that the indicator diagram from an engine enables us **to calculate the work done on the piston by the working agent** from measurements of $p$ which may be made in either of two ways:

1st, measure the average breadth of the diagram directly;

Or, 2nd, measure the area of the diagram and divide by its exact length.

1. The simplest approximate method, and the one which engineers use most frequently, is to measure the mean or average pressure from the diagram or card as follows:—Divide the distance L L′ into ten equal parts, bisect these and from the points of bisection draw ten equidistant lines at right angles to the atmospheric line as in Fig. 158. With the indicator-scale, a pair of compasses, or better still a *strip of paper*, measure or lay off successively the lengths of these

lines intercepted by the closed curve P Q R S. Add these lengths together and divide by ten gives the mean effective pressure $p$ pounds per square inch acting on the piston during the explosion stroke.

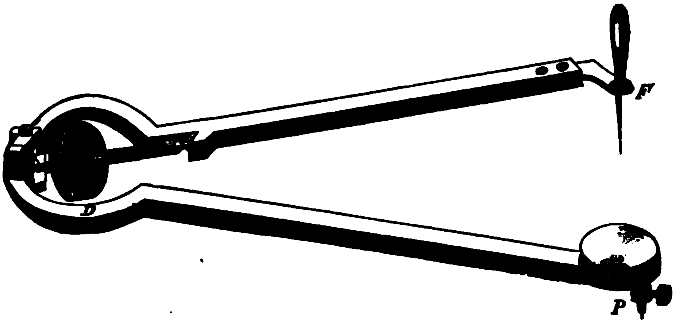
In Fig. 158, the mean height of the actual indicator diagram is 0·975 inch, and the scale of the spring used gives a compression of $\frac{1}{80}''$ for 1 lb. per square inch, therefore the mean pressure is $0{\cdot}975 \times 80 = 78$ lb. per square inch.

As this operation is likely to disfigure a diagram, it is usual to make these measurements on tracings of the original diagram. Here errors may creep in, and the addition of a series of lengths which are only approximations may also lead to slight inaccuracy, especially when the diagram is a small one from a strong indicator spring.

2. AMSLER'S POLAR PLANIMETER.—The polar planimeter, invented in 1856 by Professor Amsler, of Schaffhausen, Switzerland, is now generally used to measure the area and height of indicator diagrams where great accuracy and saving of labour is desired.

The planimeter in its simplest form, Fig. 159, consists of two bars, the radius bar P D, and the pole-arm, jointed together so as to have perfect freedom of motion in one plane. The point P in the radius bar is kept fixed, whilst the tracing point F on the pole-arm is carried *clockwise* (in the direction

FIG. 159.



THE AMSLER PLANIMETER.

the hands of a clock go) round the boundary of the diagram. The roller wheel fixed to the pole-arm partly rolls, and slips only when the tracer moves exactly in the direction of the axis of the arm. After moving the tracer F completely round the diagram back to the starting-point, the area is registered by the revolving wheel and vernier.

This roller wheel is very delicate, especially its rolling surface on the outside edge.

In using the instrument care is required to avoid undue slipping of the wheel, and the diagram should be placed on a flat even surface, as a sheet of drawing-paper, large enough for the instrument to work easily.

Sink the needle-point P into the paper at a convenient distance outside the diagram, and place a weight upon the bar to keep it in its place. Start with the point of the tracer F, Fig. 159, on any point, say S, of the diagram, Fig. 158. Adjust the wheel and vernier to zero. The tracing-point F is carefully carried clockwise round the diagram S P Q R, returning to the starting-point S.

Now, to read off the area in square inches, note the highest figure of the large divisions on the roller wheel that has passed by zero on the vernier.

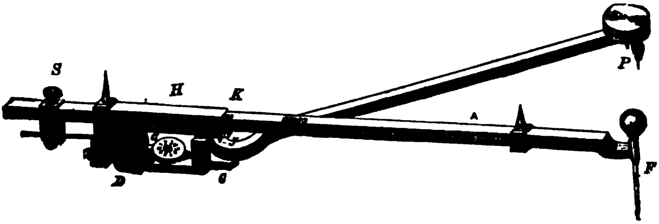
This gives the units, the small divisions are tenths, whilst the reading on the vernier that exactly coincides with a graduation on the wheel represents hundredths of square inches. The instrument only records up to 10 square inches, so that, for a large area, after the index passes zero, 10 has to be added to the reading. The accuracy of the instrument may be checked beforehand by moving the tracing point round a known regular area, and comparing the indicated value with that already calculated.

Having thus found the *area* of the indicator-diagram in square inches, divide by its length measured parallel to the atmospheric line, and we obtain the average height of the diagram. Multiply this height by the scale number of the indicator spring used in taking the diagram, and the result is the *average pressure* on the piston.

An important modification of this planimeter, shown in Fig. 160, is specially arranged to give at once the average height from an indicator diagram in fortieths of an inch.

This instrument has also a horizontal wheel G which registers the tens, the roller wheel D tenths and hundredths, whilst the vernier gives the third place of decimals. The sliding bar A or pole-arm carrying the tracer F may be varied in length by means of the sleeve H which slides along it, for the purpose of recording the area in different units, as square inches, square feet, square millimetres, and square centimetres. The vertical lines on this sliding bar have the various units marked alongside.

FIG. 160.



THE AMSLER PLANIMETER.

The instrument is set *for measuring areas* by adjusting the sleeve H so that the mark J on the inner end of it at K is exactly opposite the division on the sliding bar corresponding to the particular unit in which the area is desired. Then clamp the sliding bar by the screw at S, and proceed as above.

Next, to read the *mean height* at once from an indicator diagram. Loosen the clamp-screw S and adjust the two steel points, on the upper side of the bar A, to the extreme points of the diagram, measured on a line parallel to the atmospheric line, by inverting the instrument so that the two points take in the exact length of the diagram, then clamp the bar by the screw S.

Having thus set the sliding bar, place the planimeter in usual position on a flat surface with the point P fixed outside the diagram, trace carefully the outline by the pointer F in the direction the hands of a clock go, returning to the starting-point. Now the figures on the horizontal wheel G stand for hundreds, the roller-wheel gives tens, with the small divisions units, and the vernier decimals.

The reading is the *mean height of the diagram* in fortieths of an inch. Therefore divide by 40 to find the mean height in inches, and this quotient multiplied by the vertical scale of the diagram gives the *mean pressure* on the piston in lb. per square inch.[*]

SIMPSON'S RULE.—In case a planimeter is not available, a very near approximation to the *area* of the *indicator diagram* may be made on the assumption that the bounding curve consists of a number of parabolic arcs.

The area is calculated by what is commonly but incorrectly called **Simpson's Rule**, though pointed out by Newton.[†]

Divide the diagram into any *even* number of strips or elements of area by an *odd* number of equidistant parallel lines or ordinates drawn perpendicular to the atmospheric line. *Add together the sum of the end ordinates (usually these are of no length), twice the sum of the other odd ordinates, and four times the sum of the even ordinates; multiply the* TOTAL SUM *by one-third the common distance between any two adjacent ordinates.*

The *area*, thus found in square inches, when divided by the length of the diagram in inches, measured parallel to the atmospheric line, gives the *mean height* of the diagram.

Obviously, we may simplify this process and find the *mean height directly*, without knowing the area, *by dividing the total sum (obtained as above) by three times the number of strips into which the diagram is subdivided.* Then multiply the mean height by the scale of the indicator spring used, and the result will be the average pressure on the piston.

---

[*] For further information on the theory of the planimeter see Williamson's *Integral Calculus*; *On Amsler's Planimeter*, by Sir Frederick F. Bramwell, in the British Association Report, 1872, pp. 401–412; and *Ueber die Genauigkeit der Planimeter*, by Professor Lorber. The subject is also fully discussed in a most valuable paper on *Mechanical Integrators*, by Professor H. S. Hele Shaw, in the Minutes of Proceedings Inst. C.E., vol. lxxxii. 1885, pp. 75–163.

[†] See *Opuscula*, *Method. Diff.*, Prop. 6, Scholium.

## POWER.

We can now find the HORSE-POWER of an engine.

When we introduce the idea of *time* and compare amounts of work done by an agent in some interval of time we use the term *power, or rate of doing work.*

Watt's practical unit of power, which he called *one horse-power,* is the *rate of doing* 33,000 *foot-pounds of work per minute,* or 550 *foot-pounds per second.* This is commonly adopted for estimating the *rate of working.* It was determined by James Watt from experiments on London dray horses, allowing a safe margin for his engine, and it is about one and a half times the power of a good horse.

To find the horse-power of any agent we have simply to calculate, in foot-pounds, the work done by it in one minute, and divide by 33,000.

The *indicated horse-power* of an engine is the rate at which work is being done on the piston by the gas or working substance as calculated from the indicator diagram. To do this we require to know: (1) the diameter $d$ inches of the engine cylinder or piston, and its area $a = 0{\cdot}7854 \times d^2$ square inches; (2) the piston travel $l$ feet or twice the length of crank; and (3) the number of explosions $n$ per minute when the diagram was taken. To check the regularity of working, as well as for brake tests, we must also know (4) the speed of the engine, that is, the number of turns the crank shaft makes per minute.*

If the mean effective pressure obtained from the diagram be $p$ pounds per square inch, then $p\,a$ pounds is the total mean pressure or force urging the piston and $p\,a\,l$ foot-pounds is the effective work done by the burning gas on the piston in one complete cycle of the engine, hence the formula $p\,l\,a\,n$ gives the work in foot-pounds done on the piston per minute, where $n$ is the number of explosions per minute.

---

* The British *absolute unit of power* is that of an agent which can do work at the rate of 1 foot-poundal per second. The C. G. S. absolute unit of power is the power of an agent which can work at the rate of 1 erg per second; but this is an extremely small unit. Hence one WATT is taken as the rate of working equal to 10,000,000 ergs per second = 1 JOULE PER SECOND. 746 WATTS = 1 HORSE POWER. The French *cheval-vapeur* is 736 watts, that is, 75 kilogrammetres per second or 542 ft.-lb. per second, so that *one horse-power* = 1·014 *chevaux-vapeur.*

$$\therefore \text{Indicated horse-power} = \frac{p\,l\,a\,n}{33{,}000}.$$

Following this $p\,l\,a\,n$, we can easily calculate the indicated power of an engine.

In the special case of an Otto engine, from which the diagram Fig. 158 is taken, there is only one explosion stroke in a complete cycle, every two revolutions of the engine, when working with full load.

When running light the explosions will take place less frequently, tending to irregularity of speed.

*Example* 1.—A gas engine having 9″ diameter of cylinder and 10″ crank is running at a speed of 140 revolutions per minute, with an explosion every revolution, when an indicator diagram of mean height 0·8 inch is taken; the scale of spring is $\frac{1}{80}$″ per pound; find the indicated horse-power of the engine.

The mean pressure of gas = 80 × 0·8 = 64 lb. per sq. in.

The length of stroke or travel of piston $= \frac{10 \times 2}{12} = \frac{5}{3}$ foot.

$$\therefore \text{Indicated horse-power} = \frac{p\,l\,a\,n}{33{,}000}$$

$$= \frac{64 \times 5 \times 0{\cdot}7854 \times 9 \times 9 \times 140}{3 \times 33{,}000} = 28{\cdot}79 \text{ horse-power.}$$

—*Answer.*

*Example* 2.—From an indicator diagram we find the mean pressure on the piston is 80 lb. per square inch, the area of the piston is 85 square inches, and the length of crank 9 inches. Find the indicated horse-power when the engine is running at 154 revolutions per minute, and there is a complete cycle every two revolutions. Here the length of crank is 0·75 foot, and twice this or 1·5 foot is the length travelled by the piston in one cycle, *while work is being done on it* by the burning gas; and this occurs only every other revolution. Putting these values in our formula, we have—

$$\text{Indicated power} = \frac{80 \times 1 \cdot 5 \times 85 \times 77}{33{,}000} = 23 \cdot 8 \text{ horse-power.}$$

—*Answer.*

*Exercise* 1.—A Clerk gas engine, 7″ diameter of cylinder, 6″ crank, is making 146 revolutions per minute, with an explosion every revolution, when a diagram is taken of 0·6 inch mean height; the scale of spring is $\frac{1}{100}$″ per pound. What is the indicated horse-power?—*Answer*, 10·21 horse-power.

*Example* 3.—Given the diameter of cylinder 11 inches, the length of crank 9 inches, and the speed 160 revolutions per minute when the diagram Fig. 158 is taken. There is an explosion every alternate revolution. Find the indicated horse-power.

By the diagram we find the mean pressure 78 lb., deducting from this 1·5 lb. to allow for the average pressure during the pumping strokes, when the piston draws in the charge and expels the burning gases, we get the mean effective pressure urging the piston 76·5 lb. per square inch.

The area of piston is 11 × 11 × ·7854, or 95 square inches. Thus the total average force driving the piston is 95 × 76·5 lb.

Length of crank is 9 inches or 0·75 foot, and twice this length or 1·5 ft. is the distance through which the gases do work on the piston. Therefore the work done in one cycle is 95 × 76·5 × 1·5 foot-pounds. The speed is 160 revolutions per minute, and there are half this number or 80 cycles per minute. The rate of doing work is then 95 × 76·5 × 1·5 × 80 foot-pounds per minute, hence the horse-power is $\frac{95 \times 76 \cdot 5 \times 1 \cdot 5 \times 80}{33{,}000} = 26 \cdot 44$ horse-power.

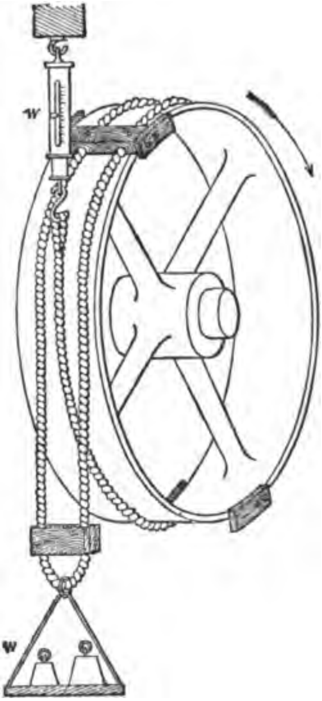
—*Answer.*

Of the total indicated horse-power in any engine, part is spent in overcoming the frictional resistances of the mechanism, and the remainder that is available for effective work is called the *useful horse-power.* This is sometimes called the

***brake horse-power***, because it is measured by a brake or dynamometer.

*Transmission dynamometers* measure the power transmitted through them by a shaft or belt from motor engines, whereas in *absorption or friction-brake dynamometers* all the power is absorbed and wasted in friction.

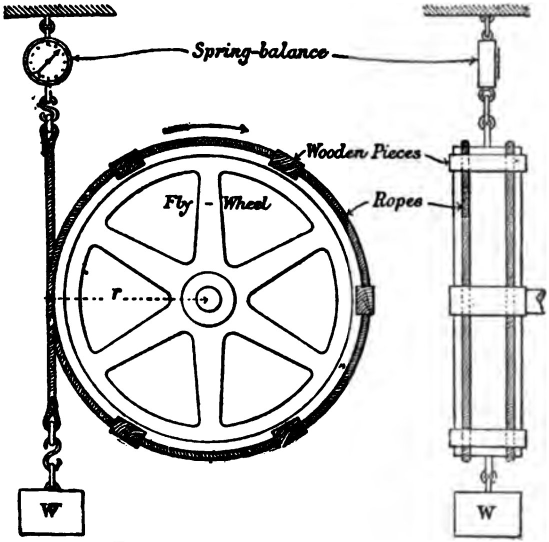
FIG. 161.



ABSORPTION DYNAMOMETER.

A simple and accurate friction-brake, as shown in Figs. 161 and 162 can readily be made in any workshop in a few minutes at a small cost. It consists of ropes kept apart, as well as from slipping off the brake-wheel, by wooden cross-pieces. These should be laced to the ropes, and not fastened by screws or metal liable to touch the rim of the wheel and become excessively heated by the friction so as to burn the rope. Grease or tallow and plumbago act as good lubricants for the wood and rope. In the case of large powers, thicker and flatter ropes or leather belt may be used with larger brake-wheel, and to avoid excessive heating, cold soapy water may be allowed to drip on the ropes to cool them by its evaporation.

FIG. 162.



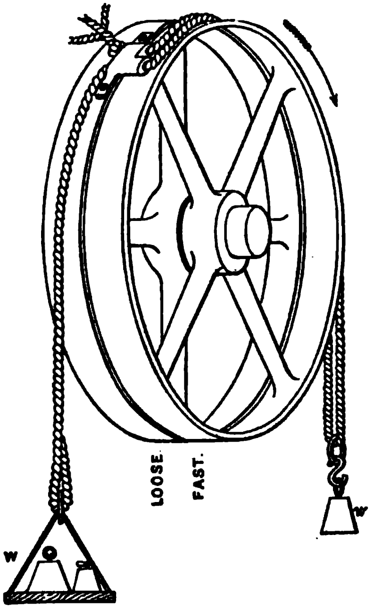
FRICTION BRAKE DYNAMOMETER.

The load is applied by means of weights in a scale pan at one end of the ropes which are passed round the wheel, and the pull in the spring-balance attached to the other end is necessary to get enough friction between the ropes and brake-wheel.

The pull on the spring-balance varies slightly to allow for any alteration in the coefficient of friction due to changes in the load or speed. A still better method of compensation for this slight change in friction is to vary the arc of contact automatically, as in a uniform-resistance brake, Fig. 163, invented by Professor James Thomson. In this the resistance is adjusted by the loose pulley being drawn round, and so unwinding part of the rope from the brake-wheel.

In both of these friction-brake dynamometers the weights must be varied to get sufficient friction at a convenient speed, which must be noted.*

FIG. 163.



THOMSON'S ABSORPTION DYNAMOMETER.

Suppose $r$ feet is the effective radius of the fly-wheel pulley or brake-wheel used, including half the thickness of the ropes, the effective circumference is $2\pi r$ feet, and when the wheel makes N turns per minute, the slipping between the ropes and pulley is $2\pi r$ N feet per minute.

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* Many other forms of dynamometer have been used. For further information the student is referred to a valuable paper and discussion on *Friction-brake Dynamometers*, by Mr. W. W. Beaumont, M. Inst. C.E., in the *Minutes of Proceedings Inst. C.E.*, vol. xcv., 1889, pp. 1–77, from which the above drawings have been taken. See also *Proceedings Inst. Mech. Eng.*, 1877, p. 237 (Mr. Froude); *Report British Assoc.*, 1883 (Prof. Unwin); *Journal of Society of Telegraph Engineers and Electricians*, vol. xii., pp. 163 and 346 (Profs. Ayrton and Perry); a series of articles in the *Electrician*, 1883–4, by Mr. Gisbert Kapp; Spons' *Dictionary of Engineering*, and Smith's *Work-measuring Machines;* Weisbach's *Mechanics of Engineering*; and a series of articles, containing useful notes on Transmission Dynamometers, in *The Mechanical World*, February till May, 1889.

The difference between the pulls on the two ends of the ropes or leather belt, that is, $W - w$, represents the net pull at the circumference of the brake-wheel, and the *work done against friction* is

$$(W - w)\, 2\pi r N \text{ foot-pounds per minute.}$$

Hence we have

$$\text{Horse-power absorbed} = \frac{(W - w)\, 2\pi r N}{33000}.$$

In other words, *the difference of the pull in a rope or belt on the two sides of a pulley, multiplied by the velocity of the rim in feet per minute, and divided by* 33,000, *gives the horse-power either absorbed or transmitted by the rope.*

Again, the difference of the pull in the rope multiplied by the radius of the pulley $(W - w) \times r$, is the total turning tendency or *torque* T necessary to overcome the friction. Also at the speed of N revolutions per minute, $2\pi N$ *radians* are turned through per minute; and $\frac{2\pi N}{60}$, the number of radians turned through per second, is usually called $\omega$ the angular velocity.

Thus the work done per second is $\omega T$, and

$$\text{Horse-power} = \frac{\omega T}{550}.$$

French engineers make measurements in kilogrammes and metres, and express the work done in kilogrammetres per second, 75 of which go to the *cheval-vapeur.*

When measurements are made by scientists in grammes' weight and centimetres, then $\omega T \div 7{\cdot}6 \times 10^6$ gives the British horse-power.

The effective power on the brake, measured in this way, usually varies from 70 to 90 per cent. of the indicated horse-power, depending upon the perfection of the mechanism and the size of the engine. In large engines the brake is about 85 per cent. of the indicated horse-power when running at less than full power.

*Nominal horse-power* is a vague commercial term used chiefly by makers of engines, to give an idea of their size. It depends on the dimensions of the cylinder and the speed of the piston, but it does not give an exact measure of the power. The indicated horse-power may be 1½, 2, or even 3 times the nominal horse-power of an engine.

# CHAPTER IX.

## ENERGY.

WE see that a gas engine does work at the expense of the gas burned in the cylinder, and the amount of work done, as indicated by the diagram, per cubic foot of gas consumed, is found to vary considerably. This is due partly to the quality and heating power of the gas used. Before we can calculate the greatest amount of heat obtainable by burning one cubic foot of any gas, we must consider the **nature and measurement of heat** as well as its transformation into work.

Any agent that is capable of doing work is said to possess a store of ENERGY. Energy is expressed in the same units as work, namely, in foot-pounds and ergs. We have seen that work is done in raising a mass against the earth's attraction; now the mass so raised has the power of doing exactly the same amount of work in *virtue of its position* relative to the earth. It is said to possess POTENTIAL ENERGY, and the work which can be got out of it in falling freely, only pulled downward by the earth, is equal to its *weight in pounds multiplied by the difference of level in feet* through which it can fall. This is neglecting the loss by frictional resistance of the air, which increases with the speed. A body weighing 100 lb., free to fall 6 ft., has stored up in it energy due to its position, or potential energy, equal in amount to 100 × 6 or 600 foot-pounds. As the mass falls it loses potential energy, but we remark its rate of motion or velocity increases. We say its potential energy is changing into *energy of motion* or KINETIC ENERGY, in virtue of which it has power to do work or overcome resistance before it is brought to rest. Thus work may be spent in communicating motion to a body, and when it has reached its lowest position and its store of potential energy is spent, then the kinetic energy produced is equivalent to the work stored up, or the potential energy lost.

As a matter of fact, there is always waste of energy, in such a change, due to friction. Part of the total store of energy in a body is continually being spent in friction producing heat, another order of energy, which becomes rapidly dissipated.

A body of mass $m$, when moving with a velocity of $v$ ft. per second, has a store of kinetic energy equal in amount to half the product of the mass into the square of its velocity,* that is,

$$\text{Kinetic Energy} = \tfrac{1}{2}\, m\, v^2 \text{ ft. lb.}$$

Since the mass of a body is its weight in pounds divided by $g$, or 32·2, it follows that

$$\text{Kinetic Energy} = \frac{\text{weight of body in lb.}}{64 \cdot 4} \times (\text{velocity})^2.$$

The kinetic energy of a mass, like a fly-wheel, rotating about an axis, depends on its dimensions, shape, and distance from the axis, and is equal to $\frac{1}{2} I \omega^2$, where I stands for the moment of inertia of the body about the axis of rotation, and $\omega$ is its angular velocity expressed in radians per second. In the case of a fly-wheel with thin broad rim, so that the greater part of the mass is distributed at nearly the same distance from the axis, the moment of inertia I = mass of the rim × (mean radius)$^2$.

As the calculation of I is usually somewhat complicated, Professor John Perry has expressed the kinetic energy of rotating bodies in the following form, which is more convenient for many practical engineers. If $n$ be the number of revolutions per minute, then the angular velocity equals $\frac{2\pi n}{60}$ radians per second, and $\frac{1}{2} I \omega^2$ becomes $\left(\frac{\pi^2 I}{1800}\right) n^2$, hence we have

$$\text{Kinetic energy stored up in a rotating body} = \mathsf{M}\, n^2 \text{ ft. lb.,}$$

where $\mathsf{M}$ is a constant, equal to $\left(\frac{\pi^2 I}{1800}\right)$, depending on the size and shape of the wheel, and may be found once for all by experiment.

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* The double of this, that is $m v^2$, is sometimes called the *vis viva*.

Two similar fly-wheels made to the same drawing but to different scales, will have their Ms in the ratio of the fifth powers of their like dimensions.

Experiment shows that *kinetic and potential energy are mutually convertible.* As a stone falls there is a continual change of potential into kinetic energy going on; and it can be proved that, if no external forces, except gravity, act on the stone, the sum of the potential and kinetic energy, at any point of its flight, remains unchanged and is equal to the original store of potential energy, so that *there is no creation or destruction of energy.*

To illustrate this, let us take a simple example. A cannon shot of 20 lb. weight fired vertically upwards with an initial velocity of 1000 feet per second, does not possess, we will suppose, any potential energy due to its position relative to the earth, at the commencement of its flight; but on leaving the cannon it has, *in virtue of its motion, kinetic energy* or power of doing work equal to

$$\tfrac{1}{2}\,\text{mass} \times (\text{velocity})^2,\ \text{that is}\ \frac{20 \times 1000 \times 1000}{2 \times 32{\cdot}2},\ \text{or } 310{,}559\ \text{ft. lb.}$$

This energy has been rapidly developed by the combustion of the charge of gunpowder, which contained a large store of *potential energy,* in virtue of the chemical arrangement of its constituents. Part of this store has been wasted in producing heat and sound. Part of the kinetic energy stored up in the shot is spent in overcoming the resistance of the air. This resistance is at first considerable, being proportional to the cube of the velocity, but rapidly decreases with the velocity. Neglecting this part of the total store of energy, which is also converted into heat, the shot has to rise against the force of gravity which is constantly acting, although with slightly diminishing intensity. At a height of 6000 feet the shot has *potential* energy equal to 6000 × 20, or 120,000 foot-pounds; the rest of the total store is still *kinetic* energy, that is, 190,559 foot-pounds. At this point the velocity of the projectile is much spent, for we know that the kinetic energy

$190{,}559 = \frac{20 \times v^2}{64 \cdot 4}$, from which we find the velocity ($v$) 783·3 feet per second.

At the highest point of its flight the shot is for an instant at rest, it has therefore no kinetic energy; this has all been exhausted in doing work against gravity, and has thus been transformed into potential energy. The shot is now in a position to have work done upon it by the attraction of gravity or downward pull of the earth. As the shot descends, its store of potential energy is reconverted into energy of motion; and when it reaches its point of projection, it should have the same velocity and therefore the same amount of kinetic energy with which it started, only for the loss by friction.

This constant change of one form of energy into another is also clearly illustrated by the *oscillation of a simple pendulum.* At the instant when the bob of the pendulum is at rest in its highest position its energy is all potential; as it falls its speed increases, and its kinetic energy also increases as the square of the speed, until at the lowest position all its energy is kinetic, and in any intermediate position part of the energy is kinetic and part potential. There is thus the continual transformation of potential into kinetic energy, whilst the total store or sum of the two remains the same, with the exception of what is wasted by friction. The same is true of the oscillations of a watch-spring, a tuning-fork, or other elastic body.

The kinetic energy of a body, at rest as a whole, may consist in the oscillations or vibratory motion of its ultimate particles or molecules, and its potential energy may be due to the *relative positions* of these particles and their mutual attraction. The molecules of a gas are *supposed* to whirl about with great velocity in all directions like little elastic balls among and against one another, keeping up an incessant bombardment against the containing vessel, and thus producing elastic pressure. Since the kinetic energy is measured by the product of the mass of a molecule into the square of its speed, it follows that the molecules of a light gas must fly or jumble about more rapidly than those of a heavier gas, to make up for the want of weight and so as to have an equal store of kinetic energy in every particle throughout a gaseous mixture.

Newton's great principle of the *conservation of energy* always holds, that is, ***the total energy of a system of bodies cannot be altered in amount by any mutual actions between its parts, although some of the total store may be transformed from one kind of energy into another.*** From this it follows that if energy of any kind be given to a system of bodies, and after a series of operations we find the whole system is exactly as it was at first, then the energy given up to other bodies during these operations must have been equal to the energy given to the system. Hence when mechanical energy is given to a system, and after certain changes the original state of things is restored, but it is found that heat has been communicated to other outside bodies by the system, and that the supply of *heat* in this way is inexhaustible, we are led to infer that mechanical energy has been transformed into ***heat which must be itself a form of energy.***

## HEAT A FORM OF ENERGY.

When a shot from a cannon hits a target, indents but does not penetrate it, the kinetic energy stored up in the shot is transformed into heat, for the shot is made very hot. If the shot passes through the target, and the kinetic energy is partly used up in overcoming resistance offered by the target and thus doing work, the shot is found not to be so much heated. True, the outside of the shot will be hot owing to the friction between it and the target, but the inside will be comparatively cool, the energy of motion (heat) having been expended in doing the work of passing through the target.

The potential energy in a mass of water capable of falling from a higher to a lower level may be utilised by allowing it to work a water-wheel. The greater part of the total store of potential energy may be first converted into kinetic energy, as in the case of an under-shot wheel, when the energy of the rapidly moving mass of water is given gradually to the wheel, and the water is left without motion, or only enough to carry it away by the tail-race, whilst the wheel does useful work by moving machinery.

The water at the bottom of the Niagara Falls is warmer than at the top, since it falls freely without doing any work. Here the potential energy of the mass of water at the top is converted into kinetic energy in falling, and this generates heat which is continually being wasted. But if the water were allowed to fall down a pipe into a turbine doing useful work, and so pass out into the tail-race, the temperature of the water at the bottom would *not* be greater than at the top. Nature is continually wasting energy in this way, changing it into heat.

### By means of Work we can produce Heat.

In fact, we find by experiment that the work done against friction has its equivalent in the vibrations of the particles of the bodies rubbed together, producing heat, sound, and electricity. A brass button rubbed briskly on a piece of wood gets hot. Savages produce fire by rubbing two pieces of dry wood together. Amongst different tribes we find some kind of *fire-drill:* the Canadian Indians have bow-drill, the Eskimos thong-drill, whilst the Zulus procure fire by vigorously rubbing and twisting or boring a dry pole between two other pieces of wood. In our own country, before the introduction of the modern safety match and percussion cap, fire was produced by striking steel against flint, the heat developed by friction being sufficient to inflame the particles of iron. When a train is stopped by applying a brake to the wheels, we usually observe a shower of sparks, and wooden brakes on a train sometimes take fire. This is due to the energy stored up in the moving train being transformed into heat by friction. The friction of driving shafts on their metal bearings often produces sufficient heat to give alarming and dangerous results when proper lubrication of the machinery is neglected. The energy given out by the engine of a steamer is re-converted into heat by the paddles or screw agitating the water as well as through the friction of the water on the skin of the ship, the effect being that the water close to the ship will be slightly warmer at the stern than at the bows. In turning a piece of metal in a lathe, and in drilling or planing machines, the point of the tool as well as the chips or pieces of metal are sometimes very hot.

In these and many other instances it is evident that the *disappearance of mechanical energy is accompanied by the production of heat.*

Reasoning about the nature of heat from facts like these Lord Bacon, in the *Novum Organum*, imagined that "heat was motion." John Locke says: "What in our sensation is *heat*, in the object is nothing but *motion.*" The early experimental school, under Gilbert, of Colchester, in 1570, regarded *heat* as a *material* substance called *caloric*, or Phlogiston, although *a body neither gains nor loses in weight by heating*, and many ingenious speculations were necessary to harmonise this idea with experiment.

Sir Benjamin Thompson, Count Rumford, was the first to show by a conclusive experiment that heat could not be material. In 1798, whilst superintending the boring of cannon at the military arsenal in Munich, he observed that a great quantity of heat was produced by the friction of the blunt steel borer on the brass castings. Rumford turned up a small cylinder, about 113 lb. weight, cast in one piece with a brass gun, and surrounded this cylinder and the end of the borer with a wooden box containing about 18·7 lb. of water at 60 F. The shavings dropped into the water. He found that the work of one horse, in rotating the brass casting and cylinder at the rate of 32 revolutions per minnte, for 2½ hours, was sufficient to raise the temperature of the water to the boiling point, besides heating the brass cylinder, boring-bar, and the rest of the machinery. After boiling water, in this way, without any fire, Rumford strenuously maintained that heat cannot be a material substance, but must consist in motion among the particles of bodies, since "*the source of heat generated by friction* in these experiments appeared evidently to be *inexhaustible*," and he proceeds:—

"It is hardly necessary to add that anything which any *insulated* body, or system of bodies, can continue to furnish *without limitation*, cannot possibly be a *material* substance; and it appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in the manner in which heat was excited and communicated in these experiments, except it be MOTION." *

In fact, from the figures given in Rumford's experiments, we can calculate approximately the *mechanical equivalent of heat* with which Joule's name is associated, and which has changed scientific thought on this subject within the last half century.

About 1798, Sir Humphry Davy melted ice by rubbing two pieces against each other in a vacuum by means of clockwork, while everything around was at a temperature below the freezing point. In this case, ice was melted and water produced above the freezing point simply by the work done in overcoming the friction of the two pieces of ice. A great quantity of heat must have been given to the ice to melt it into water, which contains a far greater amount of heat than the same mass of ice; and Davy showed that no heat had been taken from the surrounding bodies, so that this experiment is perfectly conclusive that heat cannot be a *material* substance. Davy also held that heat consisted in a peculiar repulsive motion or vibration, and in 1812 he made the following most important statement:—"The immediate cause of the phenomenon of heat is motion, and the laws of its communication are precisely the same as the laws of the communication of motion."

Moreover, the statement that "heat is *kinetic* energy" is supported by the following considerations:—

1. Heat produces changes in the volume of a body. This implies *motion*, not of the body as a whole, but of its ultimate particles. Air and gases expand, or, if prevented, increase in pressure in proportion to the heat added.

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* Rumford, vol. ii., Essay No. 9, *An Enquiry into the Source of Heat.*

2. Hot bodies communicate vibratory motion to the surrounding space, producing the sensations of heat and light, and experiment shows that these are similar in their nature and propagation. (*a*) In a homogeneous medium both are propagated in straight lines, and hence follow the law of inverse squares. (*b*) The laws of reflection and refraction are precisely the same for dark radiation as for light. A parabolic mirror reflects, and an achromatic lens concentrates, heat waves to the same focus as light waves. White light in passing through a prism is divided up into the different colours of the spectrum, increasing in wave-length from the violet to the red, and this continues in the heat part of the spectrum beyond the red, showing that the nature of the vibrations of dark radiation and light are identical, only differing in wave-length. (*c*) Both may be polarised and produce interference.

James Prescott Joule, of Manchester, was the first to prove experimentally that when heat is produced by mechanical means, the quantity of heat generated is always proportional to the quantity of energy expended; or, that the *production of one unit of heat always requires the same number of units of work to be expended.*

Doctor Joule was led to this conclusion by experiments, extending to all forms of energy, and dating from 1840. The greatest accuracy was attained in a series of *experiments** *on the friction of water,* from 1843 to 1849, and verified by similar but more delicate apparatus in 1878. The apparatus consisted of a closed cylindrical box of thin copper, filled with water, which was churned by an agitator consisting of eight vanes or paddles fixed on a vertical spindle. Inside the box there were also four stationary vanes to prevent the water being whirled round by the motion of the paddles. The agitator was made to rotate by means of a cord wound round the spindle and passing over a pulley, whose axis was supported on friction-wheels. The cord was acted upon by a mass falling through a known distance, so that the work done or energy expended could be exactly calculated in foot-pounds; corrections being made for the part spent in the friction of the apparatus, vibrations, and sound, as well as for the kinetic energy stored up in the weights on reaching the ground, and the work done by the resilience or elasticity of the string. The weights were wound up by turning a handle after detaching the spindle. This was repeated 20 times for one experiment lasting half-an-hour. Two thermometers, reading to $\frac{1}{360}$ of a degree Centigrade, were employed to give the temperature of the water before and after the churning, and that of the air in the room. Allowance was made for loss of heat by conduction, convection, and radiation from the vessel containing the water. The capacity for heat of the vessel and all it contained, including paddles, being carefully measured, and the weight of water also known, the quantity of heat required to raise these through an observed range of temperature could be calculated. After making these necessary corrections, and taking every precaution, Joule found that *the quantity of heat produced by the friction between the metal paddles and water is always proportional to the energy expended.*

---

* *Phil. Mag.*, 1843, vol. xxiii. p. 435.

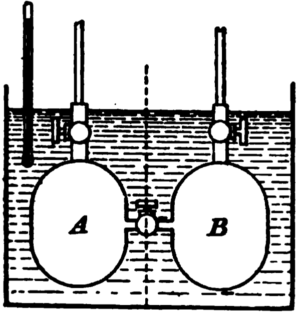
The result obtained was that 1390 *foot-pounds of mechanical energy expended entirely in friction generates one unit of heat,* that is, *the quantity of heat capable of raising the temperature of a pound's weight of water through* 1° *Centigrade is equivalent to the work done by gravity on a mass of* 1 *lb. falling through a height of* 1390 *feet,* or of 139 lb. falling 10 feet, or 1390 ft. lb. The number 1390 is called the **Mechanical Equivalent of Heat**, or **Joule's Equivalent.**

Joule tried the *friction of mercury* contained in a smaller iron vessel, and made it 1393; he also employed *cast-iron surfaces,* bevelled like parts of hollow cones, to grind against one another, heating mercury, and obtained 1395; the work being done in each case by falling weights, and all the results did not differ by more than 0·5 per cent.

In 1853, Joule verified the above results by a different method, depending on the *compression and expansion of dry air.*

He first proved that no work is done or heat consumed by air when it expands into vacuum. To do this, Joule took two copper vessels of equal capacity, connected by a short tube with stop-cock; one of them, A, Fig. 164, was filled with air, at a pressure of 22 atmospheres, and the other, B, exhausted. The whole was placed in a vessel of water, and the temperature observed when it became steady. On opening the stop-cock, the compressed air in A expanded, and rushed into the empty vessel B; but no rise or fall in the temperature of water could be detected with a thermometer reading to the $\frac{1}{360}$th of a degree Centigrade. When A and B were placed in separate vessels of water, on opening the stop-cock, the water around A became cooled and that around B warmed to the same amount; showing that the heat absorbed by part of the air as it rushed into B is given up again when that motion is partly checked; so that, on the whole, the temperature was not changed, and, therefore, there was no gain or loss of heat energy by the air. Hence no change of temperature occurs when a gas is allowed to expand without having to do any work in overcoming external resistances.

FIG. 164.



Again, Joule showed that nearly the whole of the *work spent* in suddenly compressing air *is converted into the heat evolved* by the air during compression.

On the other hand, by allowing compressed air to escape from a vessel through a very fine tube, all surrounded by water, the air forced out the water and did work against the atmospheric pressure. He found that the gas was cooled and *absorbed heat equivalent to the work done by it in expanding against constant external pressure.* In this way, Joule determined the specific heats of air.

His early investigations on the *calorific effects of magneto-electricity* date from about 1840. An electro-magnet was made of flat iron plates insulated from one another by oiled paper, and bound together by a coil of insulated copper wire wound round them and having the ends joined or short circuited. This armature was enclosed in a glass tube, and rotated by falling weights, for 15 minutes, between the poles of a powerful magnet. The energy of the electric current so produced was converted into heat in the coil which carried it. Corrections were made for external friction, loss by radiation, and convection. Joule found that the quantity of heat produced was the same as if the work done by the falling weights had been directly converted into heat by friction.

Joule also measured the *heating effect of the electric current from a battery of voltaic cells*. A piece of platinum-silver wire was doubled, coiled on a glass tube, which was placed in a vessel containing water. The ends of the coils were connected by short thick copper wires to a voltaic battery with a galvanometer in circuit. It was found that the heat generated in the circuit was proportional to the work done by the electro-motive force of the battery in sending a given quantity of electricity through the circuit. This *heat* is due to the electrical resistance of the wires, and *is proportional to the product of the resistance in ohms into the square of the strength of the electric current in amperes.*

Joule found that

$$\textit{Heat in calories} = 0{\cdot}24 \times (\textit{amperes})^2 \times \textit{ohms} \times \textit{seconds}.$$

A very fine thread of carbon, which offers great resistance to the passage of the electric current, may be made to glow, and become white hot by a great current density. This is the case in the ordinary glow lamp which consists of a thin carbon filament with its ends insulated and sealed into an exhausted glass bulb.

The *work done*, W, by an electro-motive force of $e$ volts, in sending a quantity $q$ coulombs of electricity through a circuit of $r$ ohms resistance, may be measured by the rule

$$W = eq = ect = c^2 r t,$$

where $c$ stands for current strength in amperes, and $t$ the time in seconds, that it flows.

Now the *power* developed in a circuit when one ampere flows through it, and the potential difference or electromotive force at its terminals is one volt, is called a *watt*. Hence in any circuit

$$\text{Watts} = \text{amperes} \times \text{volts},$$

and we have

I WATT = I JOULE PER SECOND = ·24 CALORIE PER SECOND.

In other words, if we take as our unit the heat required to raise the temperature of 1 lb. of water from 0° C. to 1° C., Joule's experiments show that a steady electric current, of $c$ ampères flowing through $r$ ohms resistance with an electromotive force $e$ volts at its terminals, generates

$$0{\cdot}0316\, c^2 r \textit{ units of heat per minute;}$$

whilst the power expended in the circuit is

$$\text{H.P.} = \frac{ce}{746} = 0{\cdot}00134\, ce.$$

From these determinations we see that work can be converted into heat, and no matter what transformations of energy take place, each pound degree Centigrade unit of heat generated requires the expenditure of its equivalent 1390 ft. lb. of work, or, in round numbers,

1 *unit of heat* = 1400 *foot-pounds of work.*

Such results are summarised in the

FIRST LAW OF THERMO-DYNAMICS :—

THE LAW OF EQUIVALENCE : *Heat is Work, and the relation between the unit of work and the unit of heat is expressed by a cetain number*, J, *known as Joule's Equivalent.*

Whenever W units of energy are wholly expended in generating H units of heat, the heat is always equivalent tc the energy spent, and we have

$$W = J H.$$

In the latitude of Manchester, 772 foot-pounds of work is equivalent to the British thermal unit, *or* the heat required to raise the temperature of 1 lb. of water from 50° to 51° Fahrenheit; converting this into C. G. S. units, 1 calorie, or the quantity of heat required to warm one gramme of water through 1° C., is equivalent to 41,550,000 ergs, or

1 CALORIE = 42,000,000 ergs = 4·2 joules, approximately.

## HEAT A MEASURABLE QUANTITY.

Since heat is a form of energy, we may measure any quantity of heat by its equivalent number of foot-pounds of work, and hence calculate what it is worth. Engineers reckon 1 horse-power given out by an engine costs 1*d.* per hour, or about 10*l.* per annum, that is, for 8 hours every working day.

Heat as a physical quantity must ultimately be measured by some of its numerous effects :—

Heat can, (1) Warm bodies or produce change of temperature;

(2) Change the molecular state of bodies—solids into liquids, and liquids into gases;

(3) Expand solids, liquids, and gases;

(4) Start chemical action;

(5) Cause a body to set up waves, radiation, and thus render bodies luminous;

(6) Produce thermo-electric currents;

(7) Alter the electrical resistance and magnetic properties of bodies;

(8) Do mechanical work

The first of the above effects is sometimes convenient to use; but we must bear in mind that *temperature is merely a thermal condition, property, or quality, by virtue of which heat tends to pass from one body to another.* Temperature is, therefore, measured by *degrees*, and really represents the intensity of heat in matter, that is, heat-level. When two bodies are placed in contact, and neither parts with its heat to the other, the bodies have the same temperature. The conception of heat as a quantity is quite distinct from temperature. 1 lb. of water in one vessel may be at the same temperature or heat level as 1 ton of water in another vessel, and yet contain a very different quantity of heat. Again, the tendency of water to flow from one vessel to another depends on the difference of level and not on the quantity of water; so the tendency of heat to flow from one body to another does not depend on the quantity of heat in one body or the other, but on their difference of heat-level. The two instruments used to measure these two things—heat quantity and temperature —are the *calorimeter* and *thermometer*.

The measurement of quantities of heat is called

### CALORIMETRY,

and the instrument used a *calorimeter*.

UNITS OF HEAT.—A *unit of heat is the amount of heat required to raise the temperature of* 1 *lb. of water from* 0° *C. to* 1° *C.* This is called the pound degree Centigrade thermal unit. Many British engineers, following Rankine, still use the Fahrenheit thermometer, and take as the thermal unit the amount of heat necessary to raise 1 lb. of water 1° F. In the metrical system, the unit of heat is called a *calorie* (*minor*) which is the amount of heat required to raise 1 gramme of water, of maximum density, through 1° C. Some French physicists and engineers take one kilogramme of pure water through the same range of temperature, and their unit quantity of heat is the *calorie major* = 1000 calories.

THERMAL CAPACITY.—Mix 1 lb. of water at 0° C. with 1 lb. of water at 2° C., gives 2 lb. at 1° C. The amount of heat given out by the 1 lb. in falling from 2° C. to 1° C. is capable of raising the temperature of the other pound from 0° C. to 1° C. It is also found that 1 lb. at 0° C. and 1 lb. at

4° C., make the temperature of the mixture 2° C. Now, if 1 lb. of mercury at 31° C. be mixed with 1 lb. of water at 0° C., the warmer body will give heat to the colder until both come to the same temperature. We find the temperature of the mixture 1° C. The mercury has fallen 30° C., but the water has only been raised 1° C. The quantity of heat given out by 1 lb. of mercury in cooling through 30° C. only suffices to raise the temperature of the 1 lb. of water through 1° C. Hence the *mean thermal capacity* of mercury, between these temperatures is one-thirtieth that of an equal mass of water. This difference in the capacity for heat of unit mass of different substances is due to a specific property of every substance, known as *specific heat.* This is not a happy term, it really should be the *thermal coefficient,* for the *specific heat of a substance at any temperature is the thermal capacity of unit mass of the substance at that temperature; that is, the number of units of heat required to raise* 1 *lb. of the substance through* 1° C. *at that temperature.* Thus the specific heat of water at 0° C. is unity, or, in other words,

SPECIFIC HEAT OF WATER = 1390 FT. LB. OF ENERGY.

If $w$ be the weight of a body in pounds, $s$ its mean specific heat between 0° C. and $t^\circ$ C., then

$$w\ s\ t \textit{ thermal units}$$

is the quantity of heat the body will absorb to raise its temperature from 0° C. to $t^\circ$ C., or that it will give out in falling through the same range of temperature, provided it does not change its state.

*Example.*—We observe that in a certain gas engine 3 gallons of water flow through the water-jacket per minute, entering at 16° C., and leaving at 40° C. Find the amount of heat carried off by the water, hence deduce the power wasted and its money value.

*Answer.*—Taking 10 lb. as the weight of a gallon of water, we have 30 lb. of water flowing away per minute. This has been raised through 40° − 16°, or 24° C., so that it carries off

30 × 24 or 720 units of heat per minute. Now one thermal unit is equivalent to 1390 ft. lb. of energy, therefore the water carries away 720 × 1390, or 1,000,800 ft. lb. per minute, that is $\frac{1,000,800}{33,000} = 30 \cdot 3$ horse-power. If we reckon on 8 hours a day working, this means a yearly waste or loss equivalent to upwards of 300*l.*, whilst for continuous running the loss is at the rate of three times this amount per annum.

## LATENT OR POTENTIAL HEAT.

Heat given to a body is not always accompanied by rise of temperature. This is the case with ice at 0° C. under the ordinary atmospheric pressure. 1 lb. of ice at 0° C. will absorb 80 units of heat to convert it into water at 0° C. without any rise of temperature. We have seen that 1 lb. of water at 0° C. mixed with 1 lb. of water at 80° C., gives 2 lbs. of water at 40° C.; but 1 lb. of *ice* at 0° C. and 1 lb. of water at 80° C. form 2 lbs. of water at 0° C. This experiment shows that as much heat is required to melt ice as would raise the temperature of an equal weight of water through 80° C. Here the heat has done internal work against molecular attraction in dragging the molecules of the solid further apart from each other, thus giving the particles greater freedom of motion and changing the state of the mass into a liquid, whilst the energy expended is stored up as *potential energy of molecular separation*, commonly called the *latent heat of fusion or liquefaction.* The latent heat of water is 80 units, or more exactly 79·25; that of zinc 28·1, lead 5·4, and mercury 2·8.

If we continue to heat water, exposed to atmospheric pressure, its temperature rises until the *boiling point** is reached, when the pressure of the vapour is equal to the superincumbent pressure of air on the free surface of the liquid.

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* The boiling point of water is lowered 1° C. for every 960 feet vertical ascent above the sea level.

The maximum pressure of steam in contact with water, at temperature $t^\circ$ C. is given in atmospheres by the formula $\left(\frac{40 + t^\circ}{140}\right)^5$.

Then the temperature remains stationary, and 1 lb. of water *at* 100° C. *will take* 536 *units of heat to convert the whole mass into steam at* 100° C. *without change of temperature.* This is called the *latent heat of vaporisation*, and we find that exactly the same amount of heat reappears on the condensation of 1 lb. of steam at the same temperature and pressure. Thus, if we boil 1 lb. of water, and allow all the steam formed, at the ordinary atmospheric pressure, to pass into a large vessel of cold water, we shall find that the steam gives up 536 units of heat on condensation, besides the amount of heat that it gives out in changing as water from 100° C. to the new temperature of the water in the vessel.

Regnault found that the total amount of heat required to raise 1 lb. of water from 0° C. to $t^\circ$ C. before evaporation, and then convert it into steam at this temperature, could be calculated by

$$Q = 606 \cdot 5 + 0 \cdot 305\, t^\circ.$$

Where Q is the number of units of heat, that 1 lb. of steam at $t^\circ$ C. is capable of giving out, when liquefied at constant temperature, $t^\circ$ and then cooled to 0° C. Regnault called this the *total heat of steam*, meaning thereby the amount of heat that passes out of steam in cooling to water at 0° C. But we cannot get the *whole* heat in one body to pass into another until we reduce one body below the absolute zero of temperature, which is physically impossible.

In the ordinary case, when $t^\circ$ is 100° C., we know that the heat required to raise 1 lb. of water from 0° C. to steam at 100° C., is the sum of the heat spent in warming it as water from 0° to 100°, and the latent heat absorbed in then converting the water into steam at 100° C., that is, $100 + 537 = 637$ thermal units. This agrees with Regnault's formula, $Q = 606 \cdot 5 + 0 \cdot 305 \times 100 = 637$ units.

The latent heat of vaporisation varies with the temperature at which the conversion into steam takes place, depending on the pressure; and neglecting the slight variation in the thermal capacity of water, we find the latent heat of steam at $t^\circ$ C. is $606 \cdot 5 - 0 \cdot 695\, t$.

Every substance has, in the same way, its own latent heats of fusion and vaporisation; namely, the quantities of heat necessary to change it from the solid to the liquid, and from the liquid to the gaseous state.

Andrews gives the following results of careful determinations at the ordinary atmospheric pressure:—

| Liquid. | Boiling Point. | Latent Heat of Evaporation. |
|---|---|---|
| Water .. .. .. .. .. | 100° C. | 536·0 |
| Alcohol .. .. .. | 78·4° | 202·4 |
| Ether .. .. .. .. .. | 35° | 90·5 |
| Ammonia .. .. .. | −40° | 234 |

*Example.*—Find the total quantity of heat required to raise 1 lb. of water from 0° C. to 400° C., the average temperature of the exhaust gases in a Gas Engine.

Here applying Regnault's formula, where $t°$ is 400, we find the total heat required is $606·5 + 0·305 \times 400 = 728·5$ units. Therefore every pound of water, formed by burning hydrogen in the cylinder of a gas engine, absorbs and carries off with it into the exhaust at this temperature 728·5 units of heat, equivalent to $728·5 \times 1390$, or 1,012,615 ft. lb. of energy wasted.

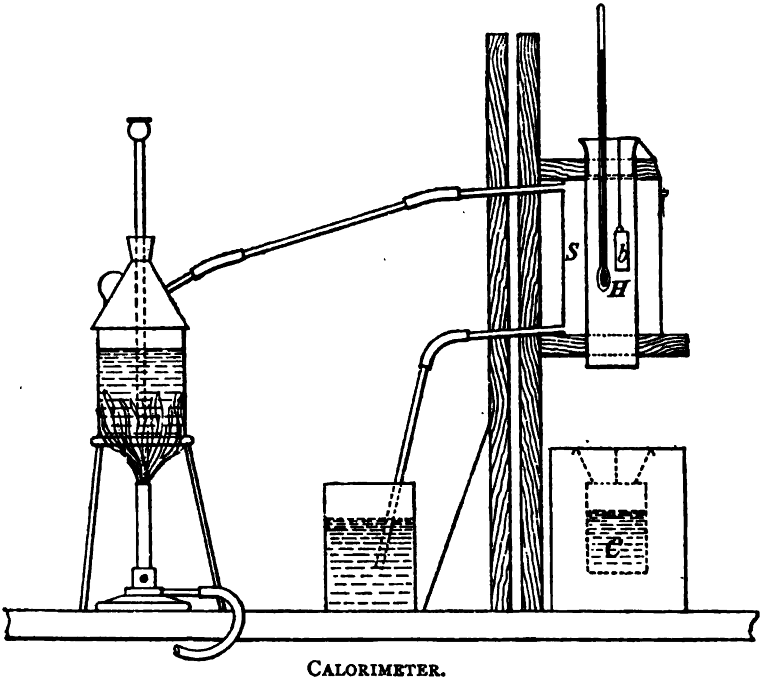
## CALORIMETRY.

We shall briefly notice *four methods of measuring heat quantities* and determining the specific heat of bodies:—

1. *The Method of Mixture* consists in mixing known weights of a hot body and of water at a lower temperature, and observing the temperature of the mixture; then the heat given out by the hot body in cooling equals the heat taken in by the cold water and calorimeter in warming, provided there has been no loss of heat.

The simple piece of apparatus, Fig. 165, is easily set up, and gives fairly accurate results. The calorimeter is a small copper or silver vessel, C, polished outside, and containing the water. It is suspended by three silk threads inside a much larger vessel, polished on both sides, and closed by a polished lid, to avoid loss of heat. There is another cylindrical vessel, or heater H, open at the bottom, and closed at the top by an indiarubber cork, through which passes a thermometer and silk thread tied to the body *b*, to be heated. This is surrounded by a larger cylinder, and steam is passed through the space S between them. Care should be taken to avoid heating the calorimeter C by this steam, hence the wooden partition with air-space is used as a screen. When the body *b* has reached a steady temperature it is lowered into the calorimeter, which is removed, and the highest temperature of the water observed. As the rise in temperature is usually not more

FIG. 165.



CALORIMETER.

than a few degrees, a delicate thermometer should be used. Equate the amount of heat absorbed by the water and calorimeter to that given out by the hot body, and the unknown specific heat is easily calculated. This is applicable to solids or liquids which do not act chemically on water.

2. METHOD OF FUSION with the Ice Calorimeter of Laplace and Lavoisier.—Here, three vessels are placed one inside the other, and the spaces between them filled with ice. The outer envelope of ice protects the inner being heated from outside, and any ice melted in this space is due to heat from the hot body. The inner vessel contains the hot body, of weight W, at a temperature $t^\circ$ C., which, in cooling to 0° C., melts ice into $w$ lb. of water to be carefully drained off and weighed, allowance being made for that lost in wetting the vessel, &c. It requires 80 units of heat to change 1 lb. of ice at 0° C. into water at 0° C.; therefore the heat given out by the hot body and absorbed by the ice is

$$w \times 80 = W x t \cdot$$

hence the required specific heat

$$x = \frac{80\, w}{W t} \cdot$$

*Bunsens's Ice Calorimeter* depends on the contraction of ice when melting.

3. METHOD OF COOLING based on Newton's Law of Cooling.—The rate of cooling by radiation is proportional to the excess of the temperature of the hot body over that of the enclosure. This is not strictly true. It is found that for the same excess temperature the rate of cooling increases with the temperature of the body, and varies greatly with the nature of the cooling surface. Therefore different materials must be covered with lamp-black to make their surfaces similar. Moreover, at low temperatures the cooling is largely due to convection currents. Increase of pressure of the air or gas around the heated body, causes it to cool more rapidly by convection. The rate at which *heat* is lost will however be

the same for all materials at the same temperature, but the rate at which the *temperature* falls will obviously depend on the specific heat of the particular material.

This method is convenient for liquids, which can be put in small copper vessels similar to calorimeters.

4. HEATING BY ELECTRICITY.—Pass an electric current of measured strength through a coil of fine wire, which imparts its heat to the surrounding liquid or gas in a calorimeter, and the quantity of

$$\text{heat generated} = \cdot 24\, c^2\, r\, t \text{ calories,}$$

where $c$ stands for strength of current in amperes, $r$ the resistance of the coil in ohms, and $t$ the time in seconds.

Observe the change in temperature of the mass, when a known quantity of heat is applied, and thus find its specific heat.

For the measurement of heat of combustion, see page 332.

## CHANGE IN SPECIFIC HEAT.

It is found that the specific heat of liquids increases with the temperature, and the same substance has a greater specific heat in the liquid than in either the solid state or gaseous state. In the case of water-substance in the solid state, as ice about the freezing point, its specific heat is 0·504; that of liquid water at 0° C. being unity; at 50° C., it is 1·0042; at 100° C. 1·013; whilst that of steam at constant pressure is only 0·48.

In gases far removed from their point of liquefaction, and hence not easily condensed, Regnault's experiments show that at constant pressure, (1) The specific heat of a gas is nearly the same at all temperatures and pressures.

(2) Equal volumes of all the simple gases at the same temperature and pressure have the same thermal capacity.

Under these circumstances, equal volumes of the simple elementary gases, hydrogen, oxygen, and nitrogen, are supposed to contain the same number of atoms, therefore *an atom of each gas has the same thermal capacity.* (See page 325.)

This is the law discovered by Dulong and Petit, that, for many elementary bodies, the product of the specific heat and atomic weight is practically constant:—

*atomic capacity = specific heat* × *atomic weight* = 6·4.

## SPECIFIC HEATS OF GASES.

Air has two specific heats, depending on whether it is kept at constant volume or at constant pressure while being heated. That at constant volume is the least and really the true specific heat. The specific heat of air at constant pressure is the amount of heat necessary to raise 1 lb. weight of air 1° C. while it is allowed to expand under constant external pressure doing external work. When a substance is in a perfectly gaseous state, the molecules are so far apart compared with their size that there is no appreciable attraction between them, consequently no work is required to separate them, and, as Joule proved experimentally (see page 285), no appreciable amount of heat is absorbed or liberated by the air while it expands into vacuum, doing no work.

Enclose 1 lb. of gas in a cylinder so that it can expand under constant atmospheric pressure. If heat be given to the gas, it will increase in volume and do work in overcoming the pressure of the atmosphere. The work done is equal to the total average pressure in pounds multiplied by the distance in feet through which the atmosphere has been pushed back. Now we know that no heat is absorbed by the gas for its own expansion, but part of the heat supplied goes to raise the temperature of the gas.

Observe the total heat required to raise the temperature through 1° C. whilst the gas is doing work in pushing back the atmosphere. This is the specific heat, $C_p$, of the gas under constant pressure. From this deduct the heat equivalent of the external work done and the remainder is the specific heat, $C_v$, of the gas at constant volume, that is, the heat necessary to raise the temperature of 1 lb. of the gas through 1° C., the volume being kept constant, and therefore no external work done.

For ordinary dry air, $C_p$ is 0·2375 heat unit, and $C_v$ is 0·1685. The difference, 0·069, is evidently the heat which disappears in producing the expansion under constant pressure, and exactly the same amount of heat would be produced by compressing the gas to its original volume.

It would be difficult to find the specific heat of air at constant volume, $C_v$, directly, but by observing $C_p$ and deducting the heat equivalent of the external work done by the air in expanding while being heated, we can readily calculate

$$C_v = C_p - \frac{\textit{external work}}{J}.$$

This is Joule's method of finding the ratio of the two specific heats, $\frac{C_p}{C_v}$, of air or gases, denoted by $\gamma$, which is a most important factor, regulating the expansion of gases, and will be required below in calculations of heat evolved and work done by them.

*Numerical Example.*—Joule took 1 gramme of dry air occupying 775·2 cubic cm. under the atmospheric pressure, 1,013,000 dynes per square cm. When warmed 1° C., it had absorbed ·2375 calories and expanded $dv = 775{\cdot}2 \times {\cdot}003665$ cubic cm., doing work against external pressure. Thus the *work done* is $p \,.\, dv = 1013000 \times 775{\cdot}2 \times {\cdot}003665$ ergs, and the *equivalent heat* is

$$\frac{p \,.\, dv}{J} = \frac{1013000 \times 775{\cdot}2 \times {\cdot}003665}{41{,}550{,}000} = {\cdot}0693 \text{ calories.}$$

Now the *real specific heat* at constant volume,

$$C_v = {\cdot}2375 - {\cdot}0693 = {\cdot}1682 \text{ calories.}$$

Hence

$$\frac{C_p}{C_v} = \frac{{\cdot}2375}{{\cdot}1682} = 1{\cdot}412 = \gamma.$$

From Regnault's determinations we have for air $\gamma = 1·409$, as given in the following table :—

SPECIFIC HEATS OF GASES.

(Water = 1.)

| Name of Gas. | Specific Heat at Constant Pressure, $C_p$. | Specific Heat at Constant Volume, $C_v$. | Ratio of Specific Heats, $\frac{C_p}{C_v} = \gamma$. |
|---|---|---|---|
| Dry air .. .. .. .. .. .. | 0·2375 | 0·1685 | 1·409 |
| Steam, $H_2O$ .. .. .. | 0·4750 | 0·399 | 1·302 |
| Hydrogen, H .. .. .. | 3·4090 | 2·412 | 1·413 |
| Oxygen, O .. .. .. .. | 0·2175 | 0·1551 | 1·403 |
| Nitrogen, N .. .. .. .. | 0·2438 | 0·173 | 1·411 |
| Carbonic oxide, CO .. .. | 0·2450 | 0·1726 | 1·416 |
| Carbonic acid, $CO_2$ .. .. | 0·2163 | 0·1712 | 1·263 |
| Marsh gas, $CH_4$ .. .. .. | 0·5929 | 0·4701 | 1·261 |
| Products of combustion of coal gas and air in the gas engine cylinder (see p. 372) | 0·2581 | 0·1889 | 1·367 |

Recent careful and elaborate experiments by Mallard and Le Chatelier point to a continuous increase in the specific heats, at constant volume, of steam, carbonic acid gas, and even of the perfect gases with rise of temperature. The variation is inappreciable about 100° C., but increases more rapidly at the high temperatures common in the gas-engine cylinder. These deductions are based on the mathematical law of loss of heat by gaseous mixtures at high temperatures during combustion, and therefore receiving heat when confined in a closed cold vessel. This cannot be strictly considered as the law of cooling of a simple gas after being first heated from an outside source.

Berthelot and Vieille have been led to the same conclusions by the results of their experiments on explosive gaseous mixtures.

These investigations indicate that the specific heat does increase with the temperature, but we have as yet little certain knowledge of the exact variation of the specific heats of different gases at very high temperatures. (See pages 453 and 455.)

# CHAPTER X.

## MEASUREMENT OF TEMPERATURE.

TEMPERATURE represents the *intensity of heat* in a body, and may be defined as that property of heat by virtue of which it tends to pass from one body to another. When two bodies are placed in contact and neither of them gains heat at the expense of the other, they are said to be at the same temperature or heat level. On the other hand, if one body gains while the other gives out heat, they are at different temperatures; and the direction of the flow of heat determines the higher temperature, just as the flow of water shows the higher level. When several bodies at different temperatures are placed in contact there is an interchange of heat, the hot bodies give out some of their heat to the colder ones, until all arrive at the same temperature or are in thermal equilibrium. Heat always tends to run down or degrade itself in this way and become dissipated throughout the universe, so as to give all bodies the same temperature. At every step or transformation in Nature heat becomes degraded in quality and less available or less useful as a form of energy, although the *quantity* remains unaltered. This is the principle of the *Dissipation of Energy*, as enunciated by Sir William Thomson.

Now we must keep clearly in view the difference between *heat*, as a form of energy, to be measured quantitatively, and the *mere sensation of warmth*, just as we distinguish between the *energy of motion* of a body, and the *sensation* caused by a blow. Sometimes, in comparing the relative temperature of bodies, we judge by how they feel to the touch, and say one is hot and another cold, but these *sensations are deceptive* and not to be relied upon, varying as they do with our state of health, the nature of the substances, and other circumstances. At best our sensations merely tell us the *relative rates* at which our finger gains or loses heat. A body at a very low temperature, as frozen mercury, and another at a very high temperature, as red hot iron, will both injure the skin and cause pain alike; the latter by giving heat to the skin, and the former by receiving heat from the skin, too rapidly. We are also perfectly familiar with the fact that bodies of different material, as wood, iron, and dry woollen cloth, may be at the same temperature and produce very different sensations when touched, depending on the rate at which they give out or receive heat, and consequently upon the relative powers of these different substances to conduct heat from warmer to colder particles in contact with them, that is, on their *relative thermal conductivity.* The *influence of last impressions* may be illustrated by a simple experiment:—Hold one hand in ice-cold water and the other in very hot water for some time; on removing them both into tepid water, the hand that was in the hot water tells us the tepid water feels cold, whilst, judging from the sensations of the other hand, we are inclined to think the tepid water is rather warm. Hence, instruments giving reliable indications must be used to aid our senses in making observations, and measuring the temperature of different bodies.

## THERMOMETERS.

In the measurement of temperature, advantage is taken of the fact that bodies generally expand, or else increase in pressure, when heated. A brass ball, when heated, will no longer pass through the ring which was an exact fit for it when cold. Mercury which nearly filled a glass bulb and tube when cold, overflows when heated, because mercury expands more than glass. A closed bladder, partially filled with cold air and shrivelled looking, becomes well filled and hard when held before the fire. The pressure of the air in the bladder having rapidly increased with the temperature, overcomes the pressure of the surrounding air in the room, but if allowed to cool, the pressure of the air diminishes and the bladder shrinks back to its original volume. If the volume be kept constant, the pressure in any mass of dry air or gas increases uniformly with the temperature, and is in fact proportional to the absolute temperature. In the more usual case of expansion at constant pressure, the temperature is indicated by change of volume; and the same amount of heat is required to raise the temperature of a given mass of air through each degree of temperature. This advantage is peculiar to the air-thermometer.

The liquid most commonly used in the ordinary thermometer for measuring temperatures is mercury, because (1) it can readily be obtained in a state of purity, and remains liquid through a wide range of temperature, i. e. from − 40° C. to 350° C.; (2) it expands uniformly for equal increments of heat between the freezing point and the boiling point of water; (3) it is a good conductor of heat, and hence quickly acquires the temperature of the body in contact with it; (4) it has a small thermal coefficient or specific heat, requiring very little heat to raise its own temperature through a given range, and consequently does not much change the temperature of the surrounding body to be measured.

Since there is a fixed definite temperature at which pure ice melts, and another fixed temperature at which pure water boils under a definite pressure, Sir Isaac Newton, in 1701, proposed as *standard temperatures the freezing point and the boiling point of water*, or, more exactly, the temperature of melting ice at ordinary atmospheric pressure, and the temperature of steam as it escapes from water boiling under the average atmospheric pressure of 14·73 lb. per square inch, or of 29·905 inches of mercury at London.

Fahrenheit, of Dantzic, about 1714, was the first to construct thermometers of uniform graduation. He selected for his zero point the lowest temperature known in his day—that of a mixture of snow and salt, which is 32 divisions on his scale below the freezing point. The range from freezing to boiling point he divided into 180°, and selected for one division a length of tube having a volume equal to $\frac{1}{10000}$th part of the bulb, so that starting at his zero and warming 32° F., the mercury expanded $\frac{32}{10000}$ths, and to the boiling point it swelled $\frac{212}{10000}$ths of its original volume. This scale is most common in English-speaking countries. Professor Celsius, of Upsala, called the boiling point of water 0° and the freezing point 100°; this, turned upside down, with the freezing point marked 0° C. and boiling point 100° C., is known as the Celsius or Centigrade scale, and from its simplicity is generally used with the metrical system by scientific men In the Réaumur scale, which is still used in Switzerland and on the Continent of Europe, the standard temperatures are marked 0° and 80°.

We may suppose one thermometer tube of crown glass with the three scales marked on it. The positions of the top of the mercury column in the glass tube will be marked at the freezing and boiling points, and denoted by the numbers 0° and 100° on the Centigrade, 0° and 80° on the Réaumur, and 32° and 212° on the Fahrenheit scale. If the bore of the tube is the same uniform size throughout, the distance between these points is divided into the corresponding number of equal parts, that is, 100, 80, and 180 respectively, called degrees; and the readings on the three scales are denoted by the letters C, R, and F respectively.

In each case the glass expands as well as the mercury when the temperature rises; so that what we really observe is the difference between these expansions. Mercury only expands 0·00018 of its volume per 1° C., whilst this co-efficient of absolute expansion of crown glass is about 0·000026. Corrections have also to be made from time to time, since the zero point is found to shift as the bulb contracts in the course of years, probably owing to molecular changes in the glass.

To convert readings from one scale into any other, we have—

$$\frac{F-32}{180}=\frac{C}{100}=\frac{R}{80},$$

as the ratio of the divisions on the three scales for any given range of temperature, and the problem is thereby reduced to a simple numerical calculation.

*Example.*—To find what temperature on the Centigrade scale corresponds to 59° F., we have

$$\frac{C}{100} = \frac{59 - 32}{180}\text{; therefore } C = \frac{5}{9}(59 - 32) = \frac{5}{9} \times 27 = 15^\circ.$$

Thus 59° F. represents the same temperature as 15 of the Centigrade degrees above the freezing point, or 15° C.

*Exercise.*—Taking a unit of heat as the amount of heat given to 1 lb. of water to raise its temperature 1° C., we find the latent heat of evaporation of 1 lb. of water under ordinary atmospheric pressure is 537 thermal units, according to the Centigrade scale. What is this amount of heat by the Fahrenheit scale? *Answer*, 966·6 thermal units.

## AIR THERMOMETER.

Mercury solidifies at about − 40° C. and boils at 350° C., so that mercurial thermometers can only be used for temperatures well within this range, as they become unreliable when the temperature approaches 300° C., and are quite useless at 360° C.

Coloured alcohol is employed for very low temperatures, as its freezing point is about − 130° C.

When different liquids are used in thermometers, it is found that although they are all made to agree at the two standard temperatures, no two of them give exactly the same reading for any intermediate temperature, inasmuch as the different liquids expand at different rates. Such thermometers must be calibrated to agree at all points on the scale by comparison with standard instruments.

If dry air be enclosed in a glass bulb and tube, and kept under constant pressure, the air expands nearly uniformly for equal increments of temperature, as indicated by the mercurial thermometer between 0° and 100° C. Above this temperature Regnault found the indications of the mercurial thermometer of crown glass differed slightly from the air thermometer, being 0°·3 too low at 200° C.; 0°·1 too low at 240° C.; 0°·2 too high at 260° C.; 1°·08 too high at 300° C., and 3° too high at 340° C. Now if equal volumes of the simple gases, hydrogen, nitrogen, oxygen, and dry air, be taken under the same pressure at 0° C., they will all occupy equal volumes at any other temperature, provided the pressure be the same. Owing to its uniform expansion, dry air is the most reliable substance known for a thermometer, to measure either high or low temperatures, in cases where extreme accuracy is required. Air expands $\frac{1}{273}$ = ·00367 of its volume for every 1° C. increase of temperature at constant pressure, and is therefore twenty times more sensitive than mercury. The specific heats of these simple gases are also sensibly the same for a considerable range of temperature.

The indications of the air thermometer are also very rapid and suited for delicate investigations.

However, this extreme sensitiveness is not unattended with disadvantages. The barometer must be observed for every reading, and the air or gas in the thermometer bulb must be preserved at atmospheric pressure, else *there is danger of alteration in volume of the bulb* due to increased pressure inside it, especially at high temperatures. The bulb is sometimes made of fine hard vitreous porcelain, but this is permanently changed in capacity when heated. When platinum is used at high temperatures, the pressure of the gas must also be kept low, as the gas is liable to diffuse through the heated platinum. In short, it requires complicated apparatus and delicate manipulation to measure a single temperature with an air thermometer, various forms of which have been devised by different experiments for special investigations.

An ABSOLUTE SCALE OF TEMPERATURE is constructed by a method altogether independent of the physical properties of the particular substance used, and deduced by Sir William Thomson from the fact that "the absolute values of two temperatures are to one another in the proportion of the heat taken in to the heat rejected, in a perfect heat engine working with a source and refrigerator at the higher and lower of the temperatures respectively." The air thermometer agrees very closely with this absolute scale. The zero of absolute temperature is that imaginary temperature at which a gas would have no heat, and consequently would exert no elastic force or pressure. We shall see (page 421) that this zero from which absolute temperatures are measured, is 273° below the freezing point on the Centigrade scale, or about $-460°$ Fahrenheit; and we get the absolute temperature T by simply adding 273 to the ordinary temperature $t°$ C., or 460 to $t°$ F. Thus $T = 273 + t°$ C., and on the Fahrenheit scale $T = 460 + t°$ F.

## PYROMETERS.

It is difficult to measure readily and accurately the very high and rapidly varying temperatures in the cylinder of the internal combustion engine. Hitherto, such high temperatures have been determined by calculation from the indicator diagram, as there is no simple and satisfactory method of direct measurement, although various devices have been proposed. We cannot use a glass vessel containing mercury, because the glass would break and the mercury boil at an early stage of the experiment.

A *pyrometer*, as the name implies, is an instrument to *measure fire*, or the high temperatures of furnaces. The substance used for this purpose must not be easily destroyed by fire—platinum and porcelain answer very well on this account.

WEDGWOOD, the great potter, used a piece of baked clay (kaolin), by its contraction* when heated, to give him a rough and ready indication of the furnace temperature. Some *pyroscopes* of this rude type, used in pottery-kilns and ovens, are simply little blocks, of special composition, which indicate particular temperatures when they commence to fuse or undergo some other change.

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* Andrews observed that some clays—compounds of silica and alumina—when heated, assume a semi-glassy appearance, undergo a permanent change, and lessen in bulk.

The **difference in the expansion of materials** by heat, may be used in various ways for pyrometers.

The temperature of very hot gases may be indicated by a pyrometer consisting of a porcelain pillar fastened at one end to a tube of metal composed of a special bronze mixture that stands heat well. This tube expands considerably when exposed to the hot gases, whilst the porcelain is scarcely changed in length ; so that, using a lever attached to the free end of the metal tube to work a toothed rack, or with other suitable arrangement to magnify the relative motion, the temperature is indicated by a pointer and suitable dial on the porcelain pillar.

Thin narrow **strips of different metals,** as platinum and silver, have been used for pyrometers, when rolled together into one ribbon and wound into the form of a flat spiral. One end of this metallic spiral is fixed, and a pointer attached to the other end. Any variation in the temperature of this spiral spring, produced either by the passage of an electric current or by hot gases, causes rotation of the free end of the spring relatively to the other. This rotation may be magnified by a pointer so as to indicate small changes in temperature.

In such instruments the platinum or other metals used must be protected from contact with very hot gases, which soon oxidize metals and destroy their elasticity.

The **simple twisted strip,** devised by Professor Perry, may be arranged to act as a pyrometer.

A strip of platinum-silver or steel is fixed at the ends, caught by the middle and twisted round until it receives a permanent set of several turns. An initial tension is then given to this strip, which causes a pointer attached to the middle to rotate ; and when subsequently heated, any rise of temperature relieves the strain and allows the pointer to turn back again through a large angle.

Very thin **carbon strips** may also be used in a similar manner to indicate and magnify a slight change due to temperature by the large rotation of a pointer.

The **melting points of metals** sometimes afford an accurate means of determining very high temperatures. Siemens observed that in the furnace, cast-steel with 1 per cent. of carbon melts at 1500° C., whilst steel boiler-plates melt between 1650° C. and 1700° C.; and the latter is near the melting point of pure platinum, 1775° C. Even the slightest trace of impurity, as iridium, causes large variations in the melting point of platinum.

Metals whose melting points are not far apart may be used to fix the range of variation of an unknown temperature within certain limits. Thus to find the temperature of the gases expelled from a combustion engine cylinder, cover the exhaust-pipe with insulating material to avoid loss of heat, and see whether a piece of zinc or antimony placed in it, close to the cylinder, will melt. Since zinc melts, but antimony does not, the temperature of the exhaust gases lies above the melting point of zinc and below that of antimony, that is, somewhere about 425° C. or 430° C. Different fusible alloys, having any required melting point, may be formed into thin rings and used for the same purpose.

Professor Seger uses a graduated series of *pyroscopes* depending upon the melting point of various materials. Between 945° C., the melting point of silver as given by Violle, and that of pure gold, 1075° C., alloys of these metals are used. An increase of 20 per cent. gold raises the melting point of the alloy 23° C. Between 1075° C. and 1775° C., twenty alloys of gold and platinum are graduated. Pyroscope No. 1 containing 90 per cent. gold, and 10 per cent. platinum, fuses at 1150° C.; whilst No. 20 fuses at 1700° C. Suppose No. 10 is completely melted at any unknown temperature, and No. 11 only commenced to fuse, then the temperature is 1400° C.

As platinum is more fusible in the presence of flinty matter, another series of *pyroscopes* are graduated, and each stamped with its melting point previously determined by the air thermometer. These are made of quartz, kaolin, white marble, and felspar—the raw materials used for glazing Berlin porcelain—thoroughly mixed together and formed with gum water into tapering blocks on triangular bases, 2·5 inches high by 0·6 inch length of side at the bottom, fixed on fireclay slabs.

Another device depends on the fact that the coefficient of expansion of a PLATINUM BAR changes very little through a wide range of temperature. The bar is fitted into a hole bored in a piece of graphite or plumbago, one end resting against the plumbago and the other pressing a plug of graphite or baked clay. When the platinum bar is placed in the furnace a record is kept of its length, as indicated by the position of the plug which is pressed against it, and the temperatures thus roughly ascertained.

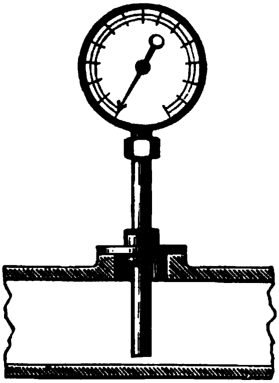
In a WATER PYROMETER, fitted for use at porcelain factories, and which indicates the temperature of pottery-kilns, water is made to flow at a constant rate through a metallic tube fixed in the place the temperature of which is required. A constant head of water is maintained, and the temperature of the in-flowing and out-flowing water observed by ordinary mercurial thermometers. The increase in the temperature of the water indicates a corresponding rise of temperature in the heated space. This instrument must be graduated in the particular substance in which it is to be used, and gives only a rough approximation. However, it may be used by an ordinary workman when once calibrated and tables arranged for different temperatures.

A pyrometer is constructed which measures, by means of an ordinary pressure gauge, the **pressure of the saturated vapour of mercury**, and Regnault's tables supply the data necessary to determine the corresponding temperatures.

The instrument consists of a metallic tube which is partly filled with mercury, and of a pressure gauge, with its scale graduated to indicate temperature directly.

The whole of the tube must be exposed to the gases in order to measure their temperature correctly. Such a pyrometer, Fig. 166, may be screwed into the exhaust pipe close to a gas engine cylinder. This instrument is perfectly reliable up to 1200° F., but must only be heated during short intervals of time, because the iron tube is rapidly oxidised at such high temperatures. Inasmuch as the *pressure of a vapour in contact with its liquid* has a fixed value for each temperature, and is independent of the size of the vessel, the indications of this instrument are not affected by any distortion which may occur in practice in the form of the tube. In this way an *average value of the temperature* can only be arrived at, as the instrument is not sufficiently quick acting to come near the highest point reached by gases which are rapidly varying in temperature.

Fig. 166.



Vapour Pressure Pyrometer.

The PLATINUM BALL PYROMETER is simply an apparatus for the *method of mixture* in calorimetry. A platinum ball of known weight and specific heat, after being exposed for some time in the furnace to the unknown temperature, is allowed to pass down a porcelain tube into a calorimeter containing a known weight of water, and the change of temperature in this is observed, hence the original temperature of the platinum ball may be calculated. This method can only afford a rough estimate of the temperature, because there must be loss of heat, (1) by the platinum ball before it reaches the water, and (2) the hot metal coming in contac with the water will convert some of it into steam. Again, the specific heats of different substances increase at different rates as the temperature rises, so that the same quantity of heat will not always produce the same rise of temperature. It is therefore necessary to find the specific heats of substances over a wide range of temperature, by independent experiment, and take every precaution to avoid loss of heat, before accurate results can be expected.

## THERMO-ELECTRIC COUPLES.

About 1822, Seebeck discovered that when one of the junctions of a closed circuit of two metals is raised to a higher temperature than the other, it tends to set up an electric current; whereas, cooling the junction reverses the direction of the current. *The electromotive force acts from high to low thermo-electric value at either junction,* and depends on, (1) the nature of the metals, (2) the difference of temperature of the two junctions, and (3) the absolute temperature of the junctions. This is modified by the Peltier effect, which is that a junction of two metals, as above, is cooled or heated by the passage of a current of electricity, according to its direction. It varies only with the absolute temperature and nature of the metals. About 1855, Sir William Thomson made the remarkable discovery that an electric current, in an unequally heated conductor, acts like a real fluid, absorbing or disengaging heat; and this is called the *electric convection of heat.* Thus heat is absorbed, when a current is flowing in copper, from the cold to the hot part of the metal; in iron the E.M.F. of this *Thomson effect* acts from hot to cold.

If one junction of a copper and iron circuit be kept at 0° C., and the other junction gradually heated, the electric current increases until a temperature of 275° C. is reached, after which the current diminishes, and becomes zero at 550° C., and on further heating the current increases in the opposite direction.

The temperature 275° C. is called the *neutral point* of the copper and iron couple.

To get a high electromotive force, increasing with the difference of temperatures of the junctions, it is advisable to use for one metal German silver, and for the other a metal like copper, having no neutral point, and with increasing difference in their thermo-electric value.

This may be clearly seen by a *thermo-electric diagram*, suggested by Sir William Thomson, and constructed by Professor Tait. Plotting vertically the values of the thermo-electric power of any metal with respect to lead at temperatures laid off horizontally, Professor Tait shows, in an elegant and simple manner, that the electromotive force of a couple is represented by an area on the diagram.

In a simple thermo-electric circuit of two metals, with the junctions at the temperatures $t°$ C. and $t_1°$ C., $t_0$ being the neutral temperature of the two metals, the total electro-motive force E is given by the empirical formula established by Avenarius:

$$E = k(t - t_1) \left\{ t_0 - \tfrac{1}{2} (t + t_1) \right\},$$

where $k$ is a constant to be determined, like $t_0$, by experiment. The electromotive force is thus proportional to the difference of temperature, and may also be increased by keeping this constant and using a greater number of junctions.

This *effect* of heat affords the most delicate means of measuring temperature. In the Nobili thermo-electric pile, several rods of bismuth and antimony are soldered together at the ends, insulated by thin paper or gutta percha, and united in the form of a cube, the alternate junctions being exposed on opposite faces. When a junction of bismuth and antimony is heated, an electro-motive force acts from bismuth to the antimony and the total electromotive in the circuit is the sum of the forces due to each pair of junctions; these, however, are only measured by the thousandth of a volt, and therefore mirror galvanometers of extremely low resistance, only a small fraction of an ohm, are suitable to give indications by reflecting a spot of light on a scale to be seen by a large audience.

Again, the *temperature of inaccessible places* may be determined by employing thick wires of iron and copper in circuit with a galvanometer. One junction is at the point of unknown temperature, and the other is placed in a vessel of water whose temperature is adjusted until there is no current through the galvanometer. Both junctions are then at the same temperature, and that of the water can be observed directly.

As the result of his experiments, M. Le Chatelier finds that a **reliable thermo-electric couple** may be made by using *fused* platinum and platinum mixed with 10 per cent. of rhodium. With a galvanometer of 250 ohms internal resistance, giving a deflection of 100 millimetres (about 4 inches) on the scale for an electromotive force of 0·01 volt, the resistance of the fused platinum and platinum-rhodium couple hardly ever exceeding 2 ohms, he obtained indications rapid enough to measure temperatures which remained constant during five seconds.

Between 300° and 1200° C. (752° and 2192° F.) the temperature is given within 10° C. by the equation

$$E = -0{\cdot}15 + 0{\cdot}115\,t,$$

where E stands for the electromotive force in volts, and *t* the temperature.

Special precautions have to be taken to ensure purity and homogeneity of the metals used, else the same couple will give variable indications under identical conditions as regards temperature.

The temperature to which the couple must be raised to give any observed electromotive force is determined by previous calibration. For this purpose the air thermometer, as well as the melting and boiling points of metals, may be used to measure standard or reference temperatures.

## SIEMENS' ELECTRICAL RESISTANCE PYROMETER.

The resistance to the passage of the electric current through a platinum wire increases with the rise of temperature, and, corresponding to any particular temperature, the same piece of wire has a constant electrical resistance.

Sir William Siemens carefully measured the electrical resistance of platinum at various temperatures within a wide range, and he found that it changes rapidly at high temperatures: thus at 450° C. a piece of platinum has 1½ times the electrical resistance that it has at 0° C., whilst at 1200° C. it has increased to 4 times its resistance at 0° C. This property of platinum is used to measure high temperatures. The resistance of a platinum wire having been ascertained for different temperatures, and a curve plotted connecting electrical *resistance* and *temperature*, if the wire is heated at any time, we have only to observe its electrical resistance and the temperature can be calculated.

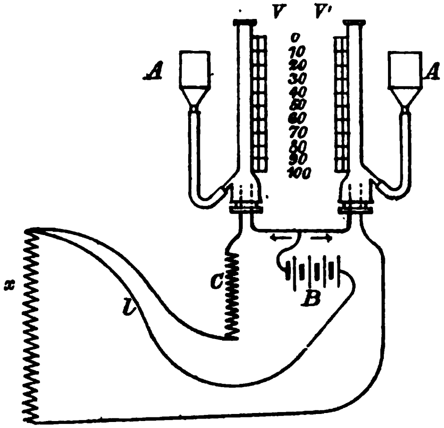
Siemens pointed out that different specimens of platinum differ greatly in resistance, depending on the process by which the platinum is prepared, and that these differences are due to the presence of small traces of other metals, chiefly iridium.

Siemens' pyrometer-coil consists of a fine platinum wire prepared by the old forging or welding process, and thoroughly annealed. This wire is wound round a piece of fire-clay, in which a spiral groove is formed to prevent the convolutions from touching one another. The little cylinder of fire-clay is inserted in a protecting case made of platinum, and fitted into the end of a long tube of wrought iron, which serves as a handle. The platinum cover protects the coil from hot gases, which would cause the platinum of the spiral wire to combine with the silicon in the fire-clay. This platinum end of the pyrometer tube is exposed to the heat to be measured. If we find the resistance $x$ of the coil when heated, we can get the temperature from Siemens' curve for this particular coil, which was compared with a mercury thermometer from 0° to 340° C. and found to be correct. At higher temperatures it was compared with a platinum ball pyrometer.

The arrangement for measuring the variable resistance $x$ of the pyrometer coil is shown in Fig 167.

V and V′ are two similar voltameter tubes with graduated scales fixed behind them. These tubes are filled with a mixture of 15 parts distilled water to one of pure sulphuric acid. The lower ends of the tubes are enlarged, and from each a branch tube is connected with a reservoir A, which may be raised or lowered until the level of the liquid in it and its fixed tube is the same, so as to have the pressure on the gases in each voltameter tube reduced to the atmospheric pressure.

FIG. 167.



SIEMENS' ELECTRICAL RESISTANCE PYROMETER.

Through the corks at the bottom, and at an equal distance apart in each tube, are two pieces of platinum foil, forming the electrodes. One electrode of each voltameter is connected with a common binding-screw, and may be joined to either pole of the battery B by turning a commutator piece (not shown in Fig. 167), and thus polarisation is prevented by reversing the current every ten seconds. The other pair of electrodes are joined up with the other pole of the battery, the one through a constant standard resistance C of thick German silver wire, and the other through the unknown variable resistance *x* of the pyrometer-coil by the leading wire *l*.

Thus the electric current flows through two branch circuits, causing decomposition of the acidulated water into hydrogen and oxygen, and these gases bubble up from the electrodes, displace the water, and accumulate in the upper portions of the two graduated tubes. At one time the current from the battery B divides at the common binding-screw, one portion passing through the acidulated water between the platinum electrodes in voltameter V, through the constant resistance C, and returning by the leading wire $l$ to the battery; the other portion flowing through voltameter V′, the platinum pyrometer coil $x$, and back by the leading wire $l$ to the battery. When the current is reversed it flows through the leading wire $l$ to the pyrometer, where it splits up, one part returning through C and V, and the other through $x$ and V′ to the battery.

The *quantity of water decomposed*, or the *volume of gas* formed in each tube in a given time, is a measure of the strength of current passing through that tube, and the ratio of the volumes of gases V and V′, reduced to the same pressure, equals the ratio of the current strengths. The resistances of the voltameters are made equal and as small as possible.

Let the resistance of each voltameter and leading wire be $r$. The constant resistance C is made as nearly as possible equal to that of the coil $x$ when hot, and is the geometrical mean of the resistances corresponding to the highest and lowest temperatures intended to be measured by the instrument. The total resistance of the pyrometer circuit is $x + r$, and the resistance of the other circuit $C + r$.

Let E be the difference of potential at the terminals of the battery B, consisting of say 5 or 6 Daniell's cells;

then $\frac{E}{C + r}$ = current in one circuit, and is proportional to V.

Also $\frac{E}{x + r}$ = current in other circuit, proportional to V′,

whence $\frac{V}{V'} = \frac{x + r}{C + r}$;

therefore $x = (C + r)\frac{V}{V'} - r$.. . . . . . . . . . (1)

This gives the resistance of the platinum coil when heated, and dividing by its known resistance at 0° C., we get the vertical ordinate of the calibration curve,* and the temperature is given by the corresponding abscissa or horizontal distance for that point on the curve.

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* See *Journal of the Society of Telegraph Engineers*, vol. iii. 1874.

In a particular pyrometer of this type employed to measure the temperature of the exhaust gases in the gas engine, the platinum coil has a resistance of 10·5 Siemens' mercury units at 0° C. The standard resistance C is 17 Siemens' mercury units, and made of German silver wire, which is very little affected by ordinary atmospheric changes of temperature. The method of joining up the pyrometer coil to the battery and voltameter, as shown in Fig. 167, is adopted to eliminate the error introduced by the heating of the leading wires. These are carried close to the platinum coil, to be equally heated, so that the total resistances are made equal in both circuits. The resistance of each voltameter is one mercury unit, and that of the leading wire in each circuit half a unit, that is, $r = 1 \cdot 5$. Thus the total resistance in the pyrometer circuit is $x + 1 \cdot 5$, and in the other circuit $17 + 1 \cdot 5$, or 18·5 mercury units. Hence equation (1) becomes

$$x = 18 \cdot 5 \frac{V}{V'} - 1 \cdot 5.$$

Dividing value of $x$ by 10·5, the resistance of the coil when cold, we find the ratio of the two resistances when hot and cold is

$$1 \cdot 762 \frac{V}{V'} - 0 \cdot 143. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The platinum end of the pyrometer having been firmly fixed in the exhaust pipe as near as possible to the cylinder, sufficient time is allowed for the platinum coil to get heated up to the average temperature of the exhaust gases. The acidulated water in the tubes V and V′ is brought to the same level 0° of scale. The battery circuit is then completed and the current allowed to pass through both voltameters, liberating the gases, which bubble up and collect in the upper part of the tubes. The commutator is turned backwards and forwards every ten seconds, reversing the current to prevent polarisation caused by the bubbles of gas sticking to the platinum electrodes. When the tubes are about half full of gases, the electric current is stopped by breaking circuit. The gases are reduced to atmospheric pressure by lowering the side reservoirs until the level of liquid in each is the same as in the corresponding tube.

The volumes V and V′, or the lengths of the two tubes occupied by the gases, are observed to be 51 and 48. Substitute these values in equation (2), and we have

$$1{\cdot}762\,\frac{51}{48} - 0{\cdot}143 = 1{\cdot}73,$$

the vertical ordinate of the calibration curve, which corresponds to 520° absolute temperature, or about 270° C.

By considering part of the curve as a straight line, we deduce the formula,

$$t^{\circ} = 594{\cdot}6\,\frac{V}{V'} - 385{\cdot}7 \quad . \quad . \quad . \quad . \quad (3)$$

which gives us a close approximation to the ordinary temperature $t^{\circ}$ C. by a single calculation, without referring to the curve. For any temperature above 200° C. the numerical value of V is greater than V′, so that this formula affords us a check for our work.

In the case when V and V′ are 51 and 48 respectively, we have

$$t^{\circ} = 594{\cdot}6 \times \frac{51}{48} - 385{\cdot}7$$

$$= 631{\cdot}7 - 385{\cdot}7$$

or $t^{\circ}$ is 246° C., the average temperature of the exhaust at a short distance from the cylinder.

During the first rush of the gases out of the cylinder, the temperature will be above this, as high as 500° C. sometimes, and during the next part of the stroke, when the flow has ceased, the temperature will fall below this to about 200° C.

We cannot by any of the above methods observe the actual temperature of the gases issuing from the cylinder with any pretence to strict accuracy, without some maximum and minimum arrangement; but the Siemens' pyrometer affords a means of determining the *average temperature* of the gases during a given interval of time, without indicating any momentary variations. In practice, however, it is found that two of these instruments exposed to very hot gases do not give concordant results, even when carefully handled.

Now, in modern gas engines, the whole explosive stroke occupies between 0·1 and 0·2 of a second, and the highest temperature is often reached in less than 0·05 of a second after the instant of ignition. Under these circumstances, an extremely sensitive and rapid indication is needed to measure at any instant the high and ever varying temperature in the cylinder. At the same time, it is most important to check the calculations of temperature from the indicator diagram by direct measurement in the engine cylinder.

The thermo-electric method tried by M. Le Chatelier (p. 313) will give the average temperature, during an interval of a few seconds, of the couple exposed to the gases escaping by the exhaust. With a suitable high resistance galvanometer and very thin sensitive couples, readings may be taken more quickly. These will give the electromotive force of the couple, and hence its temperature at the instant of making contact.

Since the couple has thermal capacity, it does not take up the temperature of the gases instantaneously, but is at a lower temperature than the gases when being heated, and at a higher temperature than them when being cooled. In order to make the couple quick acting, it should consist of exceedingly fine platinum and platinum-rhodium wires rolled into thin strips, and the junctions welded while being heated by the blow-pipe. Such extremely sensitive thermo-electric couples might be fixed in the clearance space of the gas engine cylinder, protected from contact with the hot gases, and joined up to the two coatings of a condenser with a suitable reflecting galvanometer to give an INSTANTANEOUS DEFLECTION on charging the condenser *at any desired point of the stroke*, during several successive explosions, by the engine automatically completing the electric circuit. The throw of the galvanometer is proportional to the charge held by the condenser, and the value of any given throw could be determined by comparison with one obtained from a standard cell. Having found the potential difference in volts to which the condenser has been charged by the thermoelectric couple, we know the electromotive force of the couple at any particular instant, and the corresponding temperature is determined by previous calibration.

A "first approximation" might, in this way, be made to the temperatures in the cylinder at every instant throughout the stroke. Some such arrangement is wanted to indicate the temperature of the gases in the cylinder, at every point of the cycle, as the pressure is given by the ordinary indicator.

# CHAPTER XI.

## COMBUSTION.

### LAWS OF CHEMICAL COMBINATION.

IF we pass an electric current through acidulated water, bubbles of gas are formed at the two platinum plates immersed in the water and connected with a battery of voltaic cells or other generator of electric current. Large quantities of gas may in this way be produced. If we collect the gases separately, we find about two volumes of hydrogen given off at the platinum plate by which the electric current leaves the water, for every volume of oxygen collected at the other plate by which the current enters. Moreover, the *weights* of the hydrogen and oxygen so formed always bear a fixed ratio to one another, and their sum is equal to the weight of water decomposed. It thus appears that the energy of the electric current decomposes water into its two constituent gases, which are entirely different in properties from each other and from water.

The fact that pure water is always composed of these two gases combined in this proportion may be verified by mixing two volumes of hydrogen gas with one volume of oxygen above mercury in a glass tube surrounded by a steam jacket. Passing an electric spark through the mixture causes an explosion ; the gases combine, giving out a great quantity of heat, whilst steam or gaseous water is formed. This steam, on being reduced to the original pressure and temperature, occupies two volumes, and is exactly the same weight as the hydrogen and oxygen combined.

We cannot split up hydrogen into different substances by any method or means with which we are acquainted. Hence hydrogen is called an **element**, or simple substance.

On the other hand, any body, such as water, that consists of two or more different substances chemically combined, is called a **compound**, and differs entirely in properties from its constituents.

By new and more powerful methods it may be possible to further decompose some of the bodies now regarded as elements. Up to the present time about 70 elements have been found, and these combined in various ways form all the substances—solid, liquid, and gaseous—as yet known to man. In combustion engines we shall have mainly to deal with a few of the simplest compounds of carbon, hydrogen, and oxygen.

Of the ultimate *constitution of matter* there is no sure knowledge, but physicists and chemists assume certain *hypotheses* or theories, founded on experiment, which fully and clearly explain all known physical phenomena, besides enabling us to deduce and predict other properties of matter to be verified by observation. Thus Dalton's *atomic theory* supposes that matter is made up of extremely small (hitherto undivided) particles called *atoms*. There are as many different kinds of atoms as of elements. An atom is usually represented by the first letter of the name of the element, or the first two significant letters; and this "Symbol" always denotes a certain weight known as the "Atomic weight" of the element. Now experiment shows that *each element has its own definite combining weight;* this combining weight, or a certain multiple of it, is the atomic weight. The weight of an atom of hydrogen (H) is less than that of any other known element, and is therefore taken as unity. The weight of an oxygen atom (O) is 16 times that of the hydrogen one; whilst carbon (C) is 12, and nitrogen (N) is 14 times as heavy as H.

Atoms are not usually found alone, but are supposed to be specially fond of certain other atoms with which they combine when a favourable opportunity offers, and they invariably make the same choice under identical conditions. Chemists suppose that every atom has the power of directly combining with one or more other atoms when brought into contact with them, or within infinitesimally small distance, but not till then. In this respect chemical action is unlike gravity, which acts at a distance. A group or little system of atoms forms a *molecule*, which is the smallest quantity of an element or a compound that can exist in the free state. Molecules are far too small to be seen, and have never been isolated. Sir William Thomson has estimated that if a rain-drop were magnified to the size of the earth, each constituent molecule thus magnified would be larger than a single grain of small shot, but smaller than a cricket-ball. We must bear in mind that these molecules may be only a conception of the imagination of the modern scientist; still they enable him to form a good idea of what is going on inside a mass of matter, and to give a satisfactory explanation of experimental facts. It has been proved that a molecule of most of the simple gases consists of two atoms, whilst there may be a great number of atoms in the molecule of a compound.

The **fundamental law of chemical combination** is that *all compounds are constant in composition;* in other words, the molecule of any substance has always the same atoms similarly arranged. Every molecule of pure water always consists of one atom of oxygen combined with two atoms of hydrogen, and is therefore indicated by the symbol $H_2O$. The number of hydrogen atoms is shown by the figure placed below the letter to the right, whilst a number at the beginning of the formula would tell the number of molecules.

These letters also tell the *weight* as well as nature of the substance. $H_2O$ means 18 parts by weight of the compound water, containing 2 atoms or two parts by weight of H and 1 atom or 16 parts by weight of oxygen. *The molecular weight of a compound is the sum of the atomic weights of its constituents.* Thus $CO_2$ means $12 + 2 \times 16$, that is, 44 parts by weight of carbonic acid gas; CO means 28 parts by weight of carbonic oxide; and $CH_4$ means 16 parts by weight of marsh gas.

The **second general law** is that *all substances interact chemically in fixed definite proportions by weight.*

Now since matter, like energy, is indestructible, and is merely rearranged in a chemical reaction, it is obvious the changes that take place can be represented by equations in which the *symbols* stand for the *weights*, and consequently, in the case of gases, the *volumes* of the substances. This has been proved by numerous experiments. When a substance burns in oxygen, or in common air containing oxygen, the *weight* of the compounds formed by combustion, whether gaseous or not, is equal to the weight of the original substance together with the weight of oxygen used. In fact, whenever a substance is burned in the ordinary way, oxygen enters into chemical combination, and *the weight of the products of combustion is equal to the sum of the weights of the separate substances before combustion.* For instance, when hydrogen burns or combines directly with oxygen, for every 2 lb. of hydrogen, 16 lb. of oxygen are necessary to produce water. Hence the formation of water by the combination of hydrogen and oxygen, is given by the equation

$$2H_2 + O_2 = 2H_2O \quad . \quad . \qquad (1)$$

that is, two molecules of hydrogen and one molecule of oxygen yield two molecules of gaseous water.

Taking the hydrogen atom as the unit weight, then

$H_2$ represents $2 \times 1$ parts by weight of hydrogen.
$O_2$ „ $2 \times 16$ „ „ „ oxygen.
$H_2O$ „ $2 + 16$ „ „ „ steam.

and the above equation (1) tells us that 4 parts by weight of hydrogen, completely combined with 32 parts by weight of oxygen, form 36 parts by weight of steam. This result agrees with experiment, which also shows (as above) that—

2 *volumes of hydrogen burned with* 1 *volume of oxygen yield* 2 *volumes of steam at the same temperature and pressure.*

In fact, it is found that for the gaseous compounds we have to deal with in combustion engines, *a gramme-molecule occupies the same volume as two grammes of hydrogen.* In equation (1) it is clear that the molecule of oxygen must have been made up of two atoms, which part company and combine with the hydrogen to form two separate molecules of water.

The molecular volumes of all gases are equal, and Avogadro's law states that *equal volumes of different gases at the same temperature and pressure contain the same number of molecules.* Thus the molecular weight of a compound gas always occupies twice the volume of the molecular weight of an elementary gas.

With hydrogen as unit weight, the law holds that *the density of every gaseous compound is half its molecular weight.* Now we can calculate the weight of a gas from its measured volume, having given that at 0° C. and pressure 760 mm. of mercury, 1 litre of hydrogen weighs 0·0896 grammes; that is to say, in the British engineer's units, *the weight of hydrogen is* 0·00559 *lb. per cubic foot.*

Hence, **to find the weight of a gas** in pounds per cubic foot, at the standard temperature and pressure, the rule is simply this:—

*Multiply half the molecular weight of the gas by* 0·00559.

As an example, 1 cubic foot of marsh gas ($CH_4$), at standard temperature and pressure, weighs

$$\frac{12+4}{2} \times 0{\cdot}00559\text{; that is, } 8 \times 0{\cdot}00559\text{, or } 0{\cdot}0447 \text{ lb.}$$

*Example* 1.—Find the weight in lb. of 1 cubic foot of the following gases at standard temperature and pressure:—(*a*) Olefiant gas ($C_2H_4$); (*b*), tetrylene ($C_4H_8$); (*c*), carbonic oxide ($CO$); (*d*), carbonic acid ($CO_2$); (*e*), nitrogen ($N_2$).

*Answer.*—(*a*), 0·07826 lb.; (*b*), 0·15652 lb.; (*c*), 0·07826 lb.; (*d*), 0·12298 lb.; (*e*), 0·07826 lb.

*Exercise.*—Ordinary air is a mixture of about 79 parts by volume of nitrogen to 21 of oxygen. What is the weight in lb. of 1 cubic foot of air at standard temperature and pressure? *Answer.*—0·0807 lb.

## COMBUSTION.

COMBUSTION, *or burning, is rapid chemical combination accompanied by the evolution of heat and generally of light.* When the resulting compound is decomposed, or its constituents separated into the original combustibles, an equal amount of heat is absorbed or disappears as sensible heat, being converted into what is called potential energy of atomic separation.

We shall merely consider the chemical combination of substances (combustibles) with oxygen. By the aid of chemical equations (page 368) we can deduce the proportion of oxygen to be mixed with an inflammable gas for complete combustion, in order that when the mixture is ignited it may burn so rapidly as to produce a sharp *explosion*, and no gas remains uncombined—hence the term *explosive mixture.*

Given the average composition of a gaseous fuel, we thus determine the proportion of oxygen that each constituent gas requires for complete combustion, and by adding together the portions of oxygen required by the various gases, we find the total quantity of oxygen that will be needed to completely burn the gaseous fuel in the cylinder of the combustion engine. Then, knowing that ordinary air consists of about 1 volume of oxygen to 4 of nitrogen, we may calculate the volume of air necessary to supply sufficient oxygen for the perfect combustion of any combustible gas of known composition. But the nitrogen, carbonic acid, water vapour, ammonia, and traces of other impurities present in the air materially affect the combination of the combustible gas with the oxygen, and it becomes necessary, at the outset, to know the conditions requisite for the production of a truly inflammable gaseous mixture.

### Conditions for Inflammability.

A combustible gas combines with oxygen :—

1. When the mixture contains the two gases within proper proportions.

2. When the temperature and pressure of the mixture are within fixed limits.

We have already seen that a mixture of 2 volumes of hydrogen gas with 1 volume of oxygen at atmospheric temperature (18° C.) and pressure (14·7 lb. per square inch) may be ignited by the electric spark, giving an explosion. Now if the pressure of the same mixture be reduced to 0·8 lb. per square inch at 18° C., combustion will not take place when the spark is passed; but keeping the mixture at the same constant pressure it becomes inflammable by the electric spark when heated to a high temperature.

Moreover, combustion ceases when a certain excess of either gas is added; thus 9 volumes in excess of oxygen, or 8 volumes in excess of hydrogen, added to the above mixture at 18° C., render it non-inflammable, and the only hydrogen burned is that lying in the path of the spark; but on raising the temperature of the new mixture to a certain point, it may be ignited by the spark.

Hence a mixture of hydrogen and oxygen, which will not combine at the ordinary atmospheric temperature and pressure, may be made to do so by increasing either the temperature or pressure up to certain fixed limits to be determined by experiment.

Again, at ordinary atmospheric temperature, 18° C., and pressure 14·7 lb. per square inch, a mixture of 1 volume ordinary coal gas with 13 or 14 volumes of air may be ignited by the electric spark, giving slow combustion—whilst a mixture of 1 part coal gas with 15 or 16 of air, under the same conditions, will not ignite. On the other hand, a mixture of 1 volume coal gas with 5 or 6 volumes of air at the same atmospheric temperature and pressure burns so rapidly as to give an explosion when the electric spark is passed through it. A weak, dilute mixture may, within certain limits, also become inflammable when compressed. A mixture which is explosive at a high temperature will become non-explosive by either lowering the temperature or pressure; even some of the constituents of coal gas may be made to burn and leave the rest unburnt.

It appears from experiments like these that an inert gas like nitrogen retards combustion, not only by lowering the temperature and thus diminishing the velocity of the gaseous molecules, but also by preventing contact between the molecules of the gases which act on one another. An excess of one of the combustible gases has a similar tendency, and the presence of an excess of the burnt products of the same mixture still further hinders combustion.

Experiment also shows that explosive mixtures cannot begin to combine till the constituents are brought intimately together, and a certain minimum *temperature* for each mixture is reached. This temperature, called the **ignition-point**, depends on the nature and relative proportions of the substances present. In fact, it is usually necessary to start the action. Heat must be applied by a flame or light, by friction, percussion, or in some other way. Then the substances combine directly, with evolution of heat sufficient to raise the temperature and make the combustion more and more rapid.

Spongy platinum is capable of starting the combustion of gases in air at the ordinary temperature, owing probably to the heat developed by the sudden condensation or approximation of the molecules of the combustible gases on the surface or in the minute pores of the metal. Thus a jet of hydrogen or coal gas is inflamed by contact with cold spongy platinum or palladium. The metal begins to glow as the current of gas plays on it, owing to the combustion or combination of the gases when they get intimately mixed in the fine divisions of the platinum, the temperature rises to the ignition point, and the mixture explodes. On the other hand, a jet of coal gas in the air cannot be lighted with a red hot iron.

It is necessary to add a certain proportion of air to *petroleum vapour* to obtain an explosive mixture. At the ordinary pressure and temperature a mixture of equal volumes of air and petroleum vapour will not explode. A mixture containing 3 of air to 1 of petroleum vapour gives a vigorous explosion when fired in a closed vessel; 5 volumes of air to 1 of vapour ignites with a sharp explosion; whilst 8 or 9 of air to 1 of vapour give the most highly-explosive mixture.

As an example of *how the rate of combustion depends on pressure* in the case of solids, Captain Noble has found that a pebble of gunpowder takes two seconds for its combustion in free air. The same pebble under pressure in the barrel of a gun is burned in about $\frac{1}{200}$th part of a second. The effects of different methods of firing are strikingly shown by Sir Frederick Abel with gun-cotton. A train of different forms of gun-cotton when ignited by a flame burns rapidly but harmlessly without explosion. The same train of gun-cotton when fired by a small charge of fulminate of mercury, to produce a high initial pressure, gives a most violent and dangerous explosion, due to the instantaneous change of the solid into the gaseous state, accompanied by the very great development of heat during rapid combination.

## How to Control the Rate of Combustion.

It is of the greatest practical importance to the engineer that the rate of combustion in any given engine cylinder is under control, (1) by the dilution of the mixture, (2) by the manner in which that mixture is fired, (3) by the phenomenon of dissociation, that is to say, decomposition at high temperatures followed by recombination when the temperature falls, and (4) by the cooling action of the walls of the cylinder. (See below, Chapter XV.)

Starting with a true explosive mixture we may, by diluting with air, gradually change the combination from being a rapid and violent explosion, to gradual combustion of almost particle after particle, until the mixture becomes non-inflammable.

The flame may be propagated more rapidly throughout the mixture by shooting into it a large mass of lighted gas; then combustion of a large portion of the mixture takes place at once, suddenly increasing the temperature and pressure and thus adding to the violence of the explosion.

In a gaseous mixture the rapidity of combustion, measured by the time that elapses between ignition and complete explosion as indicated by maximum pressure, depends on the richness of the mixture. A rich mixture explodes rapidly, with evolution of a great amount of heat, which is soon given up to the walls of the enclosing vessel; at the same time the very high temperatures produced split up some of the products, this is accompanied by absorption of heat, causing the pressure to fall off rapidly. A poor mixture by slow combustion does not develop so much heat all at once, and consequently not so much is wasted at first, whilst the continuous and prolonged combustion sustains the pressure.

In the internal combustion engine the cold-water jacket around the cylinder to keep it cool, also rapidly reduces the pressure unless this is sustained by continual combustion throughout the stroke.

Dr. Aimé Witz, of Lille, has studied the cooling action of the cylinder walls when the gaseous mixture is allowed to expand, driving a piston and doing external work during combustion under the same conditions as in the modern gas engine. (See page 463.) The results of his experiments show that the combustion becomes faster, and consequently the explosion pressure greater, as the velocity of expansion increases. Dr. Witz then contends that, to make use of the greatest possible part of the available heat in explosive mixtures, it is necessary to make the expansion occupy as short a time as possible, and to have the ratio of the cooling surface of the cylinder wall to the volume of the gas a minimum, so that the heat obtained from unit volume of the gas is a maximum.

Hence the great practical gain in compressing the mixture before ignition, combined with great speeds of piston to diminish the time of contact.

The cooling action suffices either to quicken or retard the combustion, so that by this means the engineer may modify or control the rate of combustion in the cylinder as well as by dilution and pressure. Again, the richness of the mixture used must vary to suit the size of cylinder and speed of piston. In the ordinary gas engine the piston makes the working part of its stroke, driven by the burning and expanding charge, in about 0·2 second.

Mr. Dugald Clerk has proved that the best mixtures, to give the highest average pressure, while burning in a closed iron vessel of cylindrical shape (7 inches diameter by 8½ inches long), and cooled by its walls without jacket, during this interval of time (0·2 seconds), are one volume of Glasgow coal gas with 11 to 13 volumes of air. In his experiments the mixtures were at the ordinary atmospheric temperature and pressure before ignition. (See page 456.)

With high speeds of piston the mixtures require to be rich in gas, to combine more rapidly and obtain the highest mean pressure throughout the working part of the stroke.

Professor Thurston found the mixture in the Otto engine to be in the ratio 7 vols. of air to 1 of lighting gas; but as the composition of both coal gas and air vary greatly in different localities, this proportion must vary accordingly.

When Dowson gas is used, the proportion of gas must be increased to about four times that of coal gas; whilst on the other hand only ½ or ⅓ the volume of oil gas suffices instead of coal gas in the existing types of combustion engine.

## HEAT OF CHEMICAL COMBINATION.

Before combustion the gaseous particles in an explosive mixture are said to possess potential energy, and when an opportunity is given them by the proper conditions being fulfilled or when they get a start, they interact in virtue of their mutual attraction, and this potential energy is, in the act of combination, converted into heat and light.

The quantities of heat developed by the combustion of various substances in oxygen have been experimentally determined with great care and ability, especially by Dr. Andrews,* by Favre and Silbermann,† and more recently by Thomsen,‡ Berthelot,§ and others.

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* *Phil. Mag.* [3], xxxii. pp. 321, 392, and 426.

† *Ann. Chim. Phys.* [3], xxxiv. p. 357, xxxvi. p. 5, xxxvii. p. 405.

‡ Thomsen's *Thermochemische Untersuchungen.*

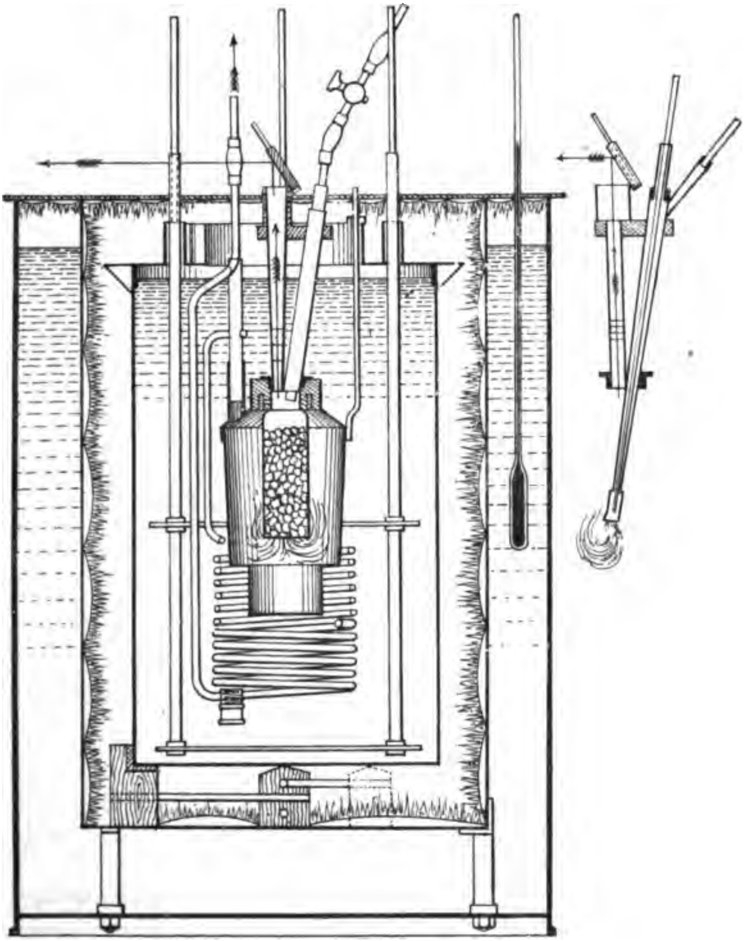
§ Berthelot's *Mécanique Chimique.*

Dr. Andrews mixed the gaseous substances to be burned with oxygen in a thin copper vessel, of 250 cubic inches capacity, surrounded by a calorimeter containing a known weight of water, kept stirred with a glass rod, and all placed in a large vessel of plate tin to prevent loss of heat by radiation and convection. The mixture was fired by the electric spark, and the rise of temperature in the water observed with a very delicate thermometer. In the case of solids, a known weight of the combustible was placed in a small platinum dish let down into the copper vessel filled with oxygen and then fired by the electric spark.

The apparatus, Fig. 168, employed by Favre and Silbermann, was more complicated. The combustion chamber was made of copper, gilt inside, and had an opening at the top, through which the combustible could be introduced with a pipe for the oxygen. The little cage which held the fuel was ⅝ inch in diameter and 2 inches high, so that only very small quantities were burned at a time—in the case of charcoal about 38 grains. A current of purified oxygen was supplied through a tube and nozzle as shown. The gradual combustion was watched through a peep-hole window closed by adiathermanous but transparent substances—alum, quartz, and glass—to prevent loss of heat. The products of combustion escaped through a thin copper coil or worm below the chamber. This was placed in a copper vessel filled with water, kept agitated. This vessel, forming the calorimeter, was silvered on the outside, and stood inside another containing swan-down, to prevent gain or loss of heat. The whole was immersed in a fourth vessel filled with water at the average temperature of the laboratory.

The carbonic acid formed in the combustion was absorbed by caustic potash. In the case of substances containing carbon, some observers overlooked the fact that a variable proportion of carbon monoxide (CO) was present among the products, rising as high as 30 per cent., showing that some of the carbon had not been completely burnt to carbon dioxide ($CO_2$), and hence corrections were necessary to determine the total heat evolved in the complete combination of the carbon with oxygen.

Fig. 168.



Calorimeter of Favre and Silbermann.

Julius Thomsen also made very careful determinations of the heat evolved in chemical actions; in some cases he used a platinum calorimeter.

Berthelot explodes the substances in an atmosphere of pure oxygen under a pressure of 25 atmospheres in a strong vessel, so that the combustion is complete, and in the case of gases instantaneous. The extra store of energy in the oxygen under such pressure tends to make the heat values obtained by combustion rather high. At the same time less heat is lost in this rapid burning than during ordinary slow combustion.

Table I. gives the heats evolved by the combustion of unit weight of the different substances, in thermal units (gramme and pound-degree centigrade), the products being cooled to the ordinary temperature :—

TABLE I.—HEATS OF COMBUSTION IN OXYGEN.

| Unit Weight of | Units of Heat Evolved. | Observer. |
|---|---|---|
| Hydrogen gas completely burned to produce liquid water at 0° C. .. .. | 34,462 | Favre and Silbermann. |
| | 33,808 | Andrews. |
| | 34,342 | Thomsen. |
| Carbon (wood charcoal) burned to form carbon dioxide at ordinary temperature 15° C... .. .. .. .. .. .. .. .. | 7,900 | Andrews. |
| | 8,137 | Berthelot |
| | 8,080 | Favre and Silbermann. |
| Carbon monoxide (CO) burned to form carbon dioxide at ordinary temperature.. | 2,403 | ,, ,, |
| | 2,431 | Andrews. |
| | 2,385 | Thomsen. |
| Marsh gas (methane $CH_4$) burned to form water and carbon dioxide .. .. .. | 13,120 | ,, |
| | 13,108 | Andrews. |
| | 13,063 | Favre and Silbermann. |
| Olefiant gas (ethylene $C_2H_4$) burned to form water and carbon dioxide .. .. .. | 11,858 | ,, ,, |
| | 11,942 | Andrews. |
| | 11,957 | Thomsen. |
| Benzol gas (benzene $C_6H_6$) completely burned to form water and carbon dioxide | 10,102 | ,, |
| | 9,915 | Favre and Silbermann. |

We see, for instance, by this table that when 1 lb. of hydrogen combines with 8 lb. of oxygen to form gaseous water, by condensing to liquid water and subsequently cooling to 0° C., the total heat evolved would raise the temperature of 34,462 lb. of water through 1° C., or the temperature of 344·62 gallons of water from 0° to 10° C. This amount of heat is not all available at higher temperatures.

According to Favre and Silbermann, 1 lb. of charcoal, in combining with $2\frac{2}{3}$ lb. of oxygen to form carbonic acid gas at the ordinary temperature, evolves heat sufficient to raise 8080 lb. of water through 1° C., that is to say,

$$8080 \times 1390 = 11,231,200 \text{ ft. lb. of energy.}$$

Dr. Andrews makes the heat thus evolved equivalent to about 10,981,000 ft. lb.

Under unusual conditions, Berthelot gets a much higher figure.

Hence we may safely reckon that 1 lb. of carbon in burning gives out 8000 units of heat, equivalent to $8000 \times 1390 = 11,120,000$ ft. lb. of energy, available for the purpose of heating water at 18° C. Since part of this heat is given out by the carbon dioxide in cooling, it is quite clear this total amount of heat cannot be utilised at higher temperatures.

# CHAPTER XII.

## FUEL.

### Solid Fuel.

It is a remarkable fact that wood fibre and starch, which look so very different, have the same ultimate chemical composition, both consisting of carbon, hydrogen, and oxygen in the same proportions as cellulose $C_6H_{10}O_5$. When wood and vegetable matter are buried in the earth, exposed to moisture and the pressure of the super-incumbent material, slow decomposition takes place, with separation of water and evolution of some carbonic acid gas at the expense of the oxygen. By this gradual process, decayed roots and leaves of vegetation, still retaining their ligneous structure, become converted into PEAT; whilst *wood*, after the application of still greater pressure, is changed into *lignite or brown coal*.

Further decomposition, with the internal heat of the earth, accompanied by the formation and discharge of marsh-gas and other hydrocarbons, changes lignite into *common or bituminous coal*.

In this way hard *anthracite* is formed, and continuation of the process ultimately yields still harder and completely fossilised coal, non-inflammable.

The different stages in the alteration of wood-fibre is shown approximately by the following table, due to Dr. Wagner:—

CONVERSION OF WOOD FIBRE INTO ANTHRACITE.

| DESCRIPTION OF FUEL. | Carbon. | Hydrogen. | Oxygen. |
|---|---|---|---|
| Wood fibre (cellulose) | 52·65 | 5·25 | 42·10 |
| Peat | 60·44 | 5·96 | 33·60 |
| Lignite | 66·96 | 5·27 | 27·76 |
| „ (brown coal) | 74·20 | 5·89 | 19·90 |
| Coal (bituminous) | 76·18 | 5·64 | 18·07 |
| „ „ | 90·50 | 5·05 | 4·40 |
| Anthracite | 92·85 | 3·96 | 3·19 |

The percentage of carbon is thus seen to increase, whilst the oxygen decreases. Bituminous coal is chiefly derived from *Sigillaroid* trees mixed with leaves of ferns. On the other hand, the structure and chemical composition of cannel coal, with spore-cases of *Lepidodendra*, point out its origin as fine vegetable mud.

The vegetation of the coal period also indicates a damp atmosphere and swampy soil, like the present cypress swamps of the Mississippi. Flowerless or *Cryptogamic* plants, *Coniferæ* large tree ferns, flourished, and *Lycopodiaceæ*, as the *Lepidodendron elegans*, whilst the stem *Sigillaria*, and leaves *Asterophyllites*, are found in abundance in the coal, and the root *Stigmaria* in the under clays of the coal seams. Amongst the *Crustacea* it is worthy of record that the three last of the *Trilobites—Brachymetopus ouralicus*, *Phillipsia pustulifera*, *Griffithides globiceps*—found a resting place in the carboniferous formation. An amphibian air-breather, the *Labyrinthodont*, left its foot-prints on the ancient sands of the coal measures, and these hand-shaped marks reveal as many as seven genera in the Kilkenny coal-field.

PEAT, or TURF, is a dark brown substance found in bogs and swampy places, chiefly in America, Ireland, and Germany, where it is used for heating purposes. It is cut from the bog in small blocks with L-shaped spades, and spread out to dry by exposure to the sun and air. Sometimes it is ground up in a machine, dried, and then compressed. It retains moisture persistently, but when dry kindles readily and burns rapidly. A light, brown, spongy peat is consumed quickly, whilst on the other hand, a black, dense variety lasts longer and gives out more heat. For complete combustion 1 lb. of peat requires the oxygen furnished by 5·64 lb. of air, though in practice twice this quantity of air is used, and 4000 units of heat are generated in the combination.

LIGNITE, or BROWN COAL, lies intermediate in appearance and properties between peat and true coal. When free from earthy matter it is very light, soft, and inferior in heating power to bituminous coal.

The following table, compiled from various reliable sources, shows the results of analyses of the different kinds of solid fuel :—

| Description of Fuel. | Composition. | | | | | | | Specific Gravity. | Total Heat Value. |
|---|---|---|---|---|---|---|---|---|---|
| | Carbon. | Hydrogen. | Oxygen. | Nitrogen. | Sulphur. | Ash. | Moisture. | | |
| Wood (air dried) .. .. .. | 40·4 | 4·9 | 32·7 | 0·9 | .. | 1·2 | .. | 0·5 to<br>1 | 3550 |
| Peat .. .. .. .. .. .. .. | 40·8 | 3·3 | 26·3 | 1·0 | .. | 7·7 | 20·9 | .. | 3774 |
| ,, (air dried) .. .. .. | 46·1 | 4·6 | 23·6 | 1·0 | .. | 1·5 | .. | 0·5 | 4250 |
| Brown coal (Bohemian) .. .. | 49·2 | 3·8 | 15·2 | .. | .. | 5·9 | 25·9 | .. | 4334 |
| Lignite (American) .. .. .. | 50·1 | 3·9 | 13·7 | 0·9 | 1·5 | 13·2 | 16·7 | 1·32 | 5718 |
| ,, (Australian) .. .. | 64·3 | 4·2 | 10·0 | 1·0 | 0·6 | 10·0 | .. | 1·27 | 6130 |
| Lump coal (Bavarian) .. .. | 57·6 | 4·4 | 18·9 | .. | .. | 11·4 | 7·7 | .. | 5716 |
| Saxon coal .. .. .. .. .. | 66·7 | 4·2 | 10·3 | .. | .. | 7·3 | 11·5 | .. | 6328 |
| Caking coal (Silesian) .. .. | 76·0 | 4·7 | 10·6 | .. | .. | 4·8 | 3·9 | .. | 7318 |
| Gas ,, ,, .. .. | 79·3 | 4·8 | 9·8 | .. | .. | 3·3 | 2·8 | .. | 7628 |
| Bituminous coal (Bohemian) .. | 72·6 | 4·9 | 10·3 | .. | .. | 4·8 | 7·4 | .. | 6832 |
| ,, ,, (Maryland, U. S.) | 80·5 | 4·5 | 2·7 | 1·1 | 1·2 | 8·3 | 1·7 | .. | .. |
| ,, ,, (Ruhr, Westphalia) | 81·6 | 4·2 | 5·5 | .. | .. | 6·0 | 2·7 | ... | 8037 |
| ,, ,, (French) .. | 84·0 | 5·0 | 8·0 | 1·1 | .. | 2·0 | .. | 1·33 | .. |
| ,, ,, (Welsh) .. | 85·0 | 4·3 | 3·5 | 1·4 | 0·4 | 5·4 | .. | .. | .. |
| Anthracite (Scotch) .. .. .. | 78·5 | 5·6 | 9·7 | 1·0 | 1·1 | 4·6 | .. | 1·26 | .. |
| ,, (Welsh) .. .. .. | 90·4 | 3·3 | 3·0 | 0·8 | 0·9 | 1·6 | .. | 1·32 | .. |
| ,, ,, .. .. .. .. | 91·5 | 3·5 | 2·6 | 0·8 | 0·6 | 1·0 | .. | .. | 8458 |
| , (Pennsylvanian) .. | 78·6 | 2·5 | 1·7 | 0·8 | 0·4 | 14·8 | 1·2 | 1·45 | .. |
| ,, (French) .. .. | 94·0 | 1·4 | 0·6 | .. | .. | 4·0 | .. | .. | .. |

## HEAT VALUE OF COAL FUEL.

The heating power of a fuel is estimated by the total quantity of heat developed in the perfect combustion of unit weight of the substance. This depends not merely on the amounts of carbon and hydrogen in the fuel, but also on the manner in which these are combined, that is, on the *chemical constitution as well as composition of the fuel.*

The *relative* heating powers of different samples of coal are sometimes more accurately estimated by their yield of coke. In order to determine the yield of coke from a given sample of coal by proximate analysis, the coal is carefully weighed and placed in a platinum crucible with a closely fitting cover, and heated for half an hour; when the volatile matter is driven off, the crucible is cooled quickly and again weighed, the percentage of coke remaining is thus found.

The density of a coal and the nature of its ash are also important indications of its quality.

In order to arrive quickly at the approximate number of heat units developed by the complete burning of 1 lb. of coal, knowing its composition, engineers usually assume that the oxygen present is combined as water with $\frac{1}{8}$th of its weight of hydrogen, which must therefore be deducted to find the available hydrogen.* Then the **total heat of combustion** of a pound of the fuel is, $8080\,C + 34462\left(H - \frac{O}{8}\right)$, where C, H, and O stand for the percentages of carbon, hydrogen, and oxygen present in the fuel. All the other constituents are neglected.

Now, 1 lb. of H is equivalent in heating power to $\frac{34462}{8080} = 4{\cdot}265$ lb. of C, so that we may write the

$$\left.\begin{array}{c}\text{Heat of combustion}\\ \text{of 1 lb. of fuel}\end{array}\right\} = 8080\left\{C + 4{\cdot}265\left(H - \frac{O}{8}\right)\right\}.$$

The **evaporative power** *of a fuel is the number of pounds of water the fuel can evaporate at atmospheric pressure and* 100° *C.* This depends on the temperature, since the latent heat of evaporation of water diminishes as the temperature rises, being 536 heat units at 100° C. Hence 1 lb. of carbon will evaporate $\frac{8080}{536} = 15 \cdot 08$ lb., or about 15 lb. of water at 100° C., and

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* A closer approximation to the heating power of fuel, as determined by calorimetric experiment, is found without making this deduction from the hydrogen. In fact, it is certain that the hydrogen in dry fuel cannot be there simply combined with oxygen as water ($H_2O$).

$$\left.\begin{array}{c}\text{Evaporative power}\\ \text{of a fuel}\end{array}\right\} = 15\left\{C + 4 \cdot 265\left(H - \frac{O}{8}\right)\right\}.$$

The total heat given out by 1 lb. of coal in burning, if it could be all utilised, would evaporate from 14 to 16 lb. of water at 1 atmosphere. Experiment shows that various substances, consisting of the same proportions of carbon and hydrogen, only differently combined, give out totally different amounts of heat in combining with oxygen. The proportion of heat spent in doing internal work, tearing the particles apart, must necessarily vary with the original arrangement of these particles in the fuel. In such cases even the relative results obtained by the above formulæ would be inaccurate.

The composition of coal varies greatly, and it is not usual in practice to submit bad specimens to chemists for testing purposes or analysis. Moreover, in careful experiments in the laboratory the oxygen or air and fuel are more intimately and thoroughly intermixed than is usual in practice when burning lumps of coal. We may, therefore, safely consider the *heating power* usually given as about 10 *per cent. above that of the average run of coal.*

For complete combustion, 1 lb. of carbon requires $\frac{32}{12}$ lb., or $2 \cdot 67$ lb. of oxygen, furnished by about 12 lb. of air, which occupies 150 cubic feet at ordinary atmospheric temperature and pressure. In careful experiments, 18 lb. of air, and in ordinary boilers as much as 24 lb. of air, is admitted for every pound of coal, so that at least 19 lb. of gaseous products are heated from the temperature of the atmosphere to that of combustion, and finally rejected at the exhaust or chimney temperature. Any water present in the fuel is evaporated, and absorbs its latent heat of evaporation, together with the heat used in raising it as liquid water to the temperature of evaporation, and finally as steam to that of the escaping products. There is loss of heat by conduction and radiation to surrounding bodies. With ordinary furnaces this loss amounts to nearly half the total heat. Besides, the temperature may be so high that dissociation prevents all the heat being developed. Energy is also spent in displacing or driving back the atmosphere. To obtain the *available heat* per pound of fuel, all such losses must be deducted from the total heat of combustion.

As a practical example, take the specimen of Ruhr coal (see composition in table, page 338). This bituminous coal was carefully burned on a fire-grate with calorimeters attached to the fire-box, and two vertical multitubular boilers covered with non-conducting material. To ensure complete combustion, about twice the calculated quantity of air was admitted to the grate, and for every pound of coal consumed 347·6 cubic feet of dry gases passed away by the chimney at 300° C. The average of thirteen experiments by Dr. Bunté gives the distribution of the heat-energy per 1 lb. of this coal:—

| | Units. |
|---|---|
| Heat given to calorimeters | 4674 |
| ,, carried away by waste gases | 1492 |
| Incomplete combustion of gaseous products | 647 |
| Heat lost by conduction and radiation | 610 |
| ,, spent in evaporating water in fuel | 283 |
| ,, lost by ashes and clinker | 331 |
| ∴ Total heat of combustion | 8037 |

We may now tabulate the *average relative* results obtained in practice by burning 1 *lb. of solid fuel.* In every case excess of air is admitted to ensure complete combustion.

| DESCRIPTION OF FUEL. | COMPOSITION. | | | Total Heating Power. | Cubic Feet of Air required per lb. of Fuel. | Cubic Feet of Air used per lb. of Fuel. | Cubic Feet of Gases in Chimney at 300° C. |
|---|---|---|---|---|---|---|---|
| | Carbon. | Hydrogen. | Ash, &c. | | | | |
| Carbon | 100 | .. | .. | 8,000 | 141 | .. | .. |
| Wood (ordinary state, 20 per cent. moisture) | 41·6 | .. | .. | 2,800 | 57·6 | 86·5 | 206 |
| Wood (dried) | 51 | 10 | 37 | 3,600 | 72 | 108 | 247 |
| Peat (dried) | 58 | 2 | 40 | 4,000 | 90 | 180 | 394 |
| Coal (average) | 88 | 5 | 7 | 7,500 | 145 | 290 | 620 |
| Anthracite | 90 | 2·4 | 7·6 | 7,350 | 145 | 290 | 620 |
| Coke | 85 | .. | 15 | 6,000 | 120 | 240 | 504 |
| Wood charcoal | 80 | 2 | 18 | 7,000 | 131 | 262 | 552 |

### COMPOSITION OF COAL AND ENERGY OF COMBINATION WITH OXYGEN.*

| Description of Fuel. | Locality. | Specific Gravity. Water = 1. | Elementary Composition. | | | Residue of Coke on Distillation (proximate analyses). | Units of heat in lb. degs. C. by 1 lb. of Coal. | Average of Equivalent Energy in foot-pounds by 1 lb. of Coal. |
|---|---|---|---|---|---|---|---|---|
| | | | Carbon. | Hydrogen. | Oxygen (by difference). | | | |
| Coke-making coal: dry with long flame | Derbyshire, Staffordshire, Lanarkshire .. | 1·25 | 75<br>to<br>80 | 5·5<br>to<br>4·5 | 19·5<br>to<br>15 | 50<br>to<br>60 | 8200<br>to<br>8300 | 11,464,200 |
| Gas coal: bituminous with long flame .. | Newcastle, Mons in Belgium, Coal Measures, Pas de Calais | 1·28<br>to<br>1·30 | 80<br>to<br>85 | 5·8<br>to<br>5 | 14·2<br>to<br>10 | 60<br>to<br>80 | 8500<br>to<br>8800 | 12,020,400 |
| True bituminous, or "Smithy coal" .. | Yorkshire, Newport in Wales .. .. .. | 1·3 | 84<br>to<br>89 | 5<br>to<br>5·5 | 11<br>to<br>5·5 | 60<br>to<br>74 | 8800<br>to<br>9300 | 12,575,880 |
| Caking coal: bituminous, with short flame .. | Near Cardiff in Wales | 1·3<br>to<br>1·35 | 88<br>to<br>91 | 5·5<br>to<br>4·5 | 6·5<br>to<br>5·5 | 74<br>to<br>82 | 9300<br>to<br>9600 | 13,131,720 |
| Anthracite coal .. .. | Charleroy, Swansea, Merthyr Tydvil .. | 1·35<br>to<br>1·40 | 90<br>to<br>93 | 4·5<br>to<br>4 | 5·5<br>to<br>3 | 82<br>to<br>90 | 9200<br>to<br>9500 | 12,992,760 |

* Compiled from data in Watts's *Dictionary of Chemistry*, vol. viii., 3rd Supplement.

We also tabulate (see preceding page) the relative quantities of heat and equivalent foot-pounds of energy that 1 lb. of the different kinds of coal will yield when completely burned in oxygen in a very careful manner.

It may be taken that 1 lb. of coal of ordinary quality in burning evolves heat equivalent to 10,000,000 ft.-lb., and that good anthracite gives out 11,000,000 ft.-lb. of energy. In addition to the constituents of coal indicated in this table, it is worthy of note that sulphur is usually present, as impurity, in quantities varying from 0·06 to 2 per cent. However, the percentage of sulphur in coke is less than in the parent coal.

The following table gives the results of most careful analyses* of the best known specimens of coal in the United Kingdom, and of the coke which each produces when heated in a closed vessel until all the gases are driven off:—

COMPOSITION OF COAL AND COKE.

| Description of Fuel. | Carbon. | Hydrogen. | Nitrogen. | Sulphur. | Oxygen (by difference). | Moisture. | Ash. | Coke per cent. by proximate Analyses. | Calculated Heat Units per lb. of Coal. |
|---|---|---|---|---|---|---|---|---|---|
| Welsh Anthracite .. .. | 89·17 | 3·50 | 0·91 | 0·96 | 1·56 | 1·78 | 2·12 | 92·12 | 8343 |
| „ „ coke .. | 88·64 | 1·37 | 0·99 | 0·63 | 0·60 | 5·60 | 2·17 | .. | .. |
| Durham coal (caking) .. | 84·34 | 5·30 | 1·73 | 0·78 | 4·29 | 1·14 | 2·42 | 71·00 | 8456 |
| „ coke .. .. .. | 87·32 | 1·67 | 1·13 | 0·75 | 1·07 | 4·36 | 3·70 | .. | .. |
| Yorkshire coal (caking) .. | 84·10 | 4·93 | 1·67 | 0·55 | 5·35 | 2·20 | 1·20 | 65·56 | 8264 |
| „ coke .. .. .. | 88·45 | 1·41 | 1·60 | 0·35 | 1·67 | 4·82 | 1·70 | .. | .. |
| English cannel coal (bastard) | 81·46 | 5·02 | 1·66 | 0·95 | 5·00 | 2·07 | 5·80 | 62·98 | 8095 |
| „ „ coke .. .. | 87·64 | 1·31 | 1·36 | 0·74 | 0·48 | 2·67 | 1·20 | .. | .. |
| Scotch cannel coal .. .. | 75·42 | 6·18 | 1·28 | 2·18 | 8·70 | 4·00 | 2·24 | 42·98 | 7850 |
| „ „ coke .. .. | 86·75 | 1·37 | 1·47 | 0·65 | 0·48 | 4·53 | 4·75 | .. | .. |

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* See paper on the *Composition and Destructive Distillation of Coal*, by Professor W. Foster, in *Minutes of Proceedings of the Institution of Civil Engineers*, vol. lxxvii., part iii., 1883–4.

## LIQUID FUEL.

**Petroleum**, or rock-oil (from *Petra*, rock, and *oleum*, oil), is the oil found in certain rocks or strata in the earth, and varies in appearance from the clear volatile liquid naphtha to heavy dark greenish slush or slime. The heavy oils are generally obtained from shallow wells, near the surface of the earth, and the lightest oils from wells bored to the greatest depths.

Four thousand years ago petroleum was used for medicinal purposes in Egypt, and its use as fuel dates from the earliest times. The mysterious flames that issued from fissures in the Caucasian Mountains, near Baku, along the Caspian Sea, were worshipped by the Magi of Asia, 600 B.C.

At the present day, on the same Apsheron * peninsula, more than 500 oil wells have been bored, 200 petroleum refineries are in operation, and this source of heat and power in Nature, which was formerly regarded with awe and reverence as the Fire-god by the disciples of Zoroaster, is now being directed by modern industry to the use and conveniance of man. In the year 1885 a small area of 1200 acres in the oil district near Baku produced 575,000,000 gallons of petroleum. A single firm, the Nobel Brothers, has over 40 oil wells, with two pipe lines 8 miles long to their refinery, which covers an area greater than a mile square at Black Town, Baku. The ordinary yield of a well is from 10,000 to 25,000 gallons a day, the supply lasting for years. The highest price of raw oil at the wells is about 1*d.* for 20 gallons, whilst the cost of refining this petroleum is at the rate of 1*d.* for every 2·5 gallons. The fuel of the Apsheron peninsula consists of the *astatki* or residual oils left from the refining process, amounting to 14 gallons from every 100 gallons of crude oil. In 1885 the export alone of this liquid fuel was 175,000,000 gallons, which represents the residuum of 5,500,000 tons crude oil from the wells.

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* See *Region of Eternal Fire; Petroleum Region of the Caspian.* By Mr. Charles Marvin, London, 1884.

The oil fields in Pennsylvania rank next in importance, the entire crude product to January 1885 being 260,990,435 barrels of 42 gallons each, and the price \$1·63⅛ per barrel.

The petroleum industry in America dates from about 1854. After Dr. Young had pointed out the way to manufacture oil from shale, the Americans established coal-oil refineries, and then discovered that an unlimited supply of petroleum was to be found by simply sinking a well, and the oil so obtained only needed refining or distillation to yield a variety of valuable products. The chief oil pools are in the Alleghany region, in the States of Pennsylvania, West Virginia, Ohio, and New York, Butler and Clarion counties, Oil Creek, Bradford City, and Pittsburgh; whilst important fields have recently been opened out in Athabasca and Mackenzie valleys in Central Canada.

The geographical and geological **distribution of petroleum** is very wide, as it occurs in almost every country, and from the lower Devonian to the recent Tertiary rocks. It is found in Alsace, Gallicia, Roumania, Russia, Persia, Egypt, India, Burma, and Japan. In England petroleum was first obtained about 1847, by Dr. James Young, from a petroleum spring in a coal mine in Derbyshire. It has also been found at Staunton in Leicestershire, at Wigan, and Coalbrookdale.

The American **well-driller**, having selected the site where he is most likely to "strike ile," erects a derrick or wooden structure, pyramidal in form, about 75 feet high, 20 feet square at the base, and tapering to 3 feet at the top. The walking beam, balanced on the Samson post and rocked by an engine, works the drilling tools—centre bit, auger stem, jars, and sinker bar—fastened thereto by temple screw and cable. The diameter of the well usually varies from an 8-inch drive pipe to 6 inches, and is drilled from 500 feet to 4000 feet deep, through the bed-rock, well into the oil sand. In American practice the well is "*shot*" or *torpedoed*, that is, a heavy charge of nitroglycerine in a canister is exploded at the bottom of the well. The effect is to disintegrate the oil-bearing strata, set free the petroleum from a larger area, and increase the yield of oil.

At Baku, on reaching the oil strata, the great pressure of the gas and oil makes it difficult to cap the well and so keep the flow under control.

Crude petroleum is brought from the wells by pipe lines 15 or 20 miles to the refineries, where it is stored in tanks under water, and allowed to stand and deposit any sediment held in suspension. Light volatile and dangerous oils are usually stored in tanks surrounded with water, to avoid explosions.

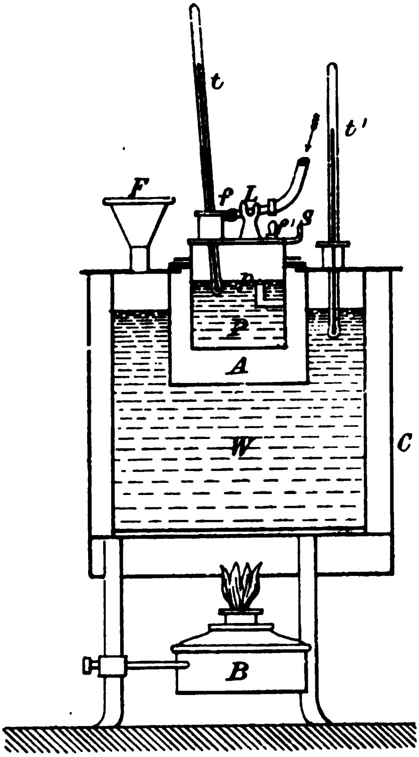
## Oil Tests.

The presence of volatile and inflammable substances, as naphtha and benzine, in petroleum renders it dangerous. The quality of oil is tested by its (1) *flashing point* and *burning point*; (2) *specific gravity*; (3) *colour*; (4) *odour*; (5) *feel* when rubbed between the fingers; (6) *yield of naphtha* on fractional distillation; and (7) the *bromine or iodine absorption tests* are very useful, as they give a comparative idea of the amount of olefines or unsaturated hydrocarbons present.

The FLASHING POINT *is the temperature at which an oil begins to give off inflammable vapours.* In England and Canada the *close test* with the apparatus of Sir Frederick Abel is the legal form, and the lowest flashing point allowed for petroleum is 73° F. or 22·8° C.

The ABEL TESTER is seen in sectional elevation, Fig. 169. The copper cylindrical vessel C contains the water bath W, filled by the funnel F, and heated to 54° C. by the lamp B. The petroleum-holder P, resting on an ebonite ring over the air-space A, has a closely-fitting cover, on which is mounted the gas-burner L, the flame $f$ being adjusted to the size of the stud $f'$, 4 millimeters long. There are three holes in the cover, opened by moving the brass slide S, and at the same time the motion of the slide, by means of a lever, tilts the burner L so as to bring the flame $f$ through a hole in the lid to the space below. The time it should be kept here is known by the swing of a pendulum bob. The oil cup P is filled to the mark *p* with the petroleum to be tested. The thermometer *t* is fixed with its bulb just covered in the oil.

FIG. 169.



ABEL TESTER.

When the temperature is 19° C., the slide is drawn to bring the flame *f* under the lid ; and this is repeated as the temperature is raised until the petroleum vapour gives a blue flash, when the test flame is applied.

In 1879 the SAYBOLT ELECTRIC TESTER was adopted in New York. Here a battery of voltaic cells and an induction coil is used to pass an electric spark $\frac{1}{8}$ inch above the surface of the oil, which is heated by a water bath. The advantage claimed is that the petroleum vapour is not so much heated by the electric spark as by a gas flame.

*The higher the flashing point, the safer is the oil.* A fall of one inch in the barometer lowers the flashing point of kerosene about 2° F. There is no international standard flashing point. The lowest limit in America and Austria is 37·5° C.; in France and Switzerland, 35° C.; Russia, 28° C.; Germany, 21° C.

The *ignition point*, commonly called *burning point*, *is the lowest temperature at which the oil takes fire.* A small percentage of benzine added to an oil will lower the flashing point considerably without much affecting the ignition point.

The term *specific gravity* means *relative density*, that is to say, the weight of a substance as compared with the weight of the same bulk of water at 4° C.

The *specific gravity* of oil is readily determined by means of an ordinary direct-reading hydrometer. A suitable hydrometer is put into the oil, and if it floats, the scale reading at the surface is simply observed and noted.

**Chemically**, petroleum is a mixture of various hydrocarbons of the paraffin series, having the general formula $C_nH_{2n+2}$, of which marsh gas $CH_4$ is the first member. There are also usually present some of the olefine ($C_nH_{2n}$) series as $C_2H_4$, and traces of the benzene ($C_nH_{2n-6}$) series. *

An average assay of Russian petroleum, 0·826 specific gravity, manufactured by the "Ragosine oil" company, shows the yield of the chief products from 100 gallons crude oil. (See table, next page.)

American petroleum is usually two or three times richer than Russian in illuminating oils, but has not so large a yield of the heavy lubricating oils.

Raw petroleum, from the wells, is split up by a series of **fractional distillations** into several products: (1) *benzine*, (2) *kerosene*, (3) *higher paraffins*, leaving (4) *residue.*

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* Care must be taken not to confound the terms "**benzene**" and "**benzine.**" **Benzene** is the hydro-carbon, $C_6H_6$, obtained in the distillation of coal tar. **Benzine**, or benzoline, is the more volatile portion of paraffin oil, and does not contain **benzene**.

RUSSIAN PETROLEUM.

| Products. | Gallons. | Specific Gravity. | Flashing Point, Centigrade. |
|---|---|---|---|
| Benzine, light oil | 1 | 0·725 | – 10° |
| Gasoline, or heavy benzine | 3 | ·775 | 0 |
| Kerosene, illuminating oil | 27 | ·822 | 25 |
| Pyro-naphtha | 12 | ·858 | 105 |
| Veregenni, lubricating oil | 10 | ·890 | 150 |
| Lubricating oil | 17 | ·905 | 175 |
| Cylinder oil, lubricating | 5 | ·915 | 200 |
| Vaseline | 1 | ·925 | |
| Residuum (LIQUID FUEL) | 14 | | |
| Loss | 10 | | |

With a gentle fire the volatile petroleum ether distillates that pass over first have the lowest boiling point, specific gravity, and flashing point; and as the temperature of the still is increased, the heavier products are separated.

When the *benzine* "runnings" of gravity up to ·730 are disposed of, the heavier kerosene oils are directed into a special tank. The fire is urged and regulated mainly by the colour of the distillate until the specific gravity of the *kerosene* oil has reached ·810. The heavy oil remaining in the still is now "cracked," that is, decomposed by destructive distillation into light illuminating oil, gas, carbon, and residuum.

The residuum is further distilled, and paraffin oil pours from the tail pipe of the condenser to be used in the manufacture of paraffin wax and lubricating oils.

The light products that first came off are again distilled, partially in vacuum, yielding rhigolene and chymogene, gasoline, and "benzine"-naphtha, or polishing oils.

In the **refining process**, the kerosene distillate is deodorised and decolourised by treatment with sulphuric acid, which settles down with the impurities as a heavy black liquid, and is withdrawn to the sludge acid tank. The oil is next washed with water, treated with caustic soda to neutralise the acid, and again washed with water. Finally, to volatilise any traces of light oils present, the oil is agitated by air pumped through it, and by a spraying process. In this way good white illuminating oil is prepared to stand the ordinary tests.

Crude American petroleum of specific gravity ·800 may thus be split up by fractional distillation as follows:—

| Temperature of Distillation. | DISTILLATE. | Percentage. | Specific Gravity. | Flashing Point. |
|---|---|---|---|---|
| 45° C. | Rhigolene | traces | ·590 to ·625 | |
| 45° to 60° | Chymogene | | | |
| 60° to 70° | Gasoline (Petroleum spirit) | 1·5 | ·636 to ·657 | |
| 70° to 120° | "Benzine"-Naphtha "C" (Benzolene) | 10 | ·680 to ·700 | − 10°C. |
| 120° to 170° | "Benzine"-Naphtha "B" | 2·5 | ·714 to ·718 | |
| | ,, ,, "A" (Polishing oils) | 2 | ·725 to ·737 | 0° |
| 170° and upwards | Kerosene (Lamp oil) | 50 | ·802 to ·820 | 38° to 50° |
| 250° | Lubricating oil | 15 | ·850 to ·915 | 110° |
| | Paraffin wax | 2 | | |
| | Residue and loss | 16 | | |

At Baku, in Russia, the heavy residual oil left in the still after the burning oil has been run off is about 60 per cent. of the original "charge," and there are 14 gallons of astatki, or residue from the refining processes, for every 100 gallons of crude oil direct from the wells. *This heavy petroleum refuse is the liquid fuel.*

In Scotland, the yellow oil refuse of heavy paraffin from the distillers is of specific gravity ·840 to ·860, and flashing point about 105° C. These "*intermediate oils*," so called because in flashing point and density they lie between burning oils and heavy lubricating oils, are used for **gaseous fuel.**

In 1850, Dr. James Young discovered that an oil like petroleum was produced by the distillation of "petroleum peat," or shale ; and along with the geologist, E. W. Binney, Young successfully distilled oil from a highly bituminous coal at Boghead, in Scotland. Shale is found in abundance in the county of Linlithgow, and one of the richest fields is at Broxburn, about twelve miles west from Edinburgh.

**Crude shale oil** is obtained by the destructive distillation of bituminous shale at 320° to 370° C. A large proportion of the gas produced is condensed to an olive green strongly-smelling viscous liquid, of density ·865 to ·870. Want of uniformity in the temperature of the still seriously affects the quality of the oil.

This **Scotch shale** oil closely resembles petroleum, and when subjected to fractional distillation and cleansed by sulphuric acid, caustic soda, and water-washings, yields the following products :—

PRODUCTS FROM SCOTCH SHALE OIL.

| Products. | Percentage (Volume). | Specific Gravity. |
|---|---|---|
| "Benzene"-Naphtha (Benzolene) .. | 5 | ·730 |
| Kerosene (Lamp oil) .. .. | 35 | ·800 to ·810 |
| Intermediate oil .. .. .. | 2 | ·850 |
| Lubricating oil .. .. .. | 18 | ·885 |
| Paraffin wax.. .. .. .. | 12 | .. |
| Coke, gas, and loss .. .. | 28 | .. |

Besides shale oil, other similar hydrocarbons, as *blast furnace oil*, *creosote*, and *tar oil*, are obtained by the condensation of the hydrocarbon gases driven off during the process of coking.

## HEAT VALUE OF LIQUID FUEL.

The constitution of ordinary petroleum is so complex, uncertain, and variable, that the exact heat value of any particular sample of oil can only be determined by direct experiment. Any refractory and porous material, as pumice stone or asbestos, may be used to hold the oil in the calorimeter crucible. In 1869 and 1871, St. Claire Deville tested many specimens of petroleum, with the idea of utilising it as a fuel. The results obtained from experiments on a large scale, and under the ordinary working conditions in locomotive practice, are still more trustworthy.

The following table gives the ultimate analyses and heat values of the different kinds of liquid fuel :—

| Description of Fuel. | Locality. | Specific Gravity. | Composition. | | | Heat Value per lb. of Fuel. | Authority. |
|---|---|---|---|---|---|---|---|
| | | | C. | H. | O (by difference). | | |
| Heavy crude petroleum | Russia (Baku) | 0·938 | 86·6 | 12·3 | 1·1 | 11,200 | St. Claire Deville. |
| ,, ,, ,, | ,, ,, | ,, | ,, | ,, | ,, | 10,820 | Gulishambaroff. |
| Light ,, ,, | ,, ,, | 0·884 | 86·3 | 13·6 | 0·1 | 11,480 | ,, |
| ,, ,, ,, | ,, ,, | 0·884 | 86·9 | 13·6 | 0·1 | 11,660 | St. Claire Deville. |
| ,, ,, ,, | ,, ,, | 0·882 | 87·4 | 12·5 | 0·1 | 11,370 | ,, |
| Crude petroleum .. | ,, ,, | 0·897 | 86·5 | 12·0 | 1·5 | 11,060 | ,, |
| ,, ,, .. | ,, ,, | 0·928 | 87·1 | 11·7 | 1·2 | 11,000 | ,, |
| Astatki (Petroleum residue) .. .. .. | ,, ,, | .. | 84·9 | 13·9 | 1·2 | 10,340 | Allen. |
| Heavy crude petroleum | Pennsylvania | 0·886 | 84·9 | 13·7 | 1·4 | 10,680 | Luglio. |
| Common petroleum .. | Virginia .. | .. | 88·3 | 13·9 | 0·8 | 10,102 | Valerius. |
| Residue ,, (Astatki) .. .. .. | ,, .. | 0·928 | 87·1 | 11·7 | 1·2 | 10,680 | ,, |
| Shale oil .. .. .. | Scotland .. | 0·860 | 86·5 | 7·0 | 0·5 | .. | Church. |
| Blast furnace oil (coke ovens) .. .. | Glasgow .. | .. | 83·5 | 10·6 | 5·9 | 8,935 | Allen. |

These figures show that the average heating power of petroleum may be taken as about 11,000 heat units per 1 lb. of oil.

## RELATIVE HEAT VALUE OF LIQUID AND SOLID FUEL.

Experiment has shown that the heating power of petroleum refuse is much greater than that of ordinary coal, besides giving higher temperatures.

In locomotive practice, an evaporative power of 7 to 7·5 lb. of water per lb. of coal is generally obtained; that is, 60 per cent. of the heating power of the coal is utilised, whilst the remaining 40 per cent. is lost. About the Caspian Sea, where petroleum refuse (crude astatki) is extensively used in locomotives and steamers, 1 lb. of this liquid fuel evaporates 12 to 14 lb. of water under ordinary conditions. This represents an efficiency of 75 to 80 per cent.

Taking the price of coal as 12*s.* 6*d.* per ton delivered, 1*d.* worth of coal is 15 lb., this in burning gives out 15 × 7500 heat units, of which 60 per cent. is realised in locomotives, that is, $15 \times 7500 \times \cdot 6 = 67{,}500$ heat units.

Now, one gallon of petroleum, specific gravity 0·830, weighs 8·3 lb. and evolves in burning 8·3 × 11,000 heat units, giving $8\cdot 3 \times 11{,}000 \times \cdot 75 = 68{,}475$ heat units actually realised. Hence, to compete with coal *under these conditions*, the price of petroleum must not exceed 1*d.* per gallon, or 22*s.* 6*d.* per ton.

Engineer-in-Chief B. F. Isherwood, of the United States Navy, made experiments with petroleum as a fuel on board the gunboat *Pallas*, and in his report claims the following advantages for liquid over solid fuel:—(1) A reduction of 40·5 per cent. in weight of fuel. (2) Reduction of 36·5 per cent. in bulk, which means a large saving of space in the hold of a vessel. (3) Greater facilities in storage, including convenience and speed in loading a supply of fuel. (4) Reduction in the number of "stokers" (firemen) to one-quarter—a large saving of hard labour. (5) Greater speed in kindling fires and getting up steam. (6) Instantaneous extinction of furnace fires. (7) More uniform and complete combustion, giving higher temperatures.

On the other hand, the disadvantages attending the use of petroleum as a fuel are:—(1) Loss of fuel by evaporation. (2) Danger of explosions from inflammable vapours. (3) Increase in the price of crude oil.

Mr. Urquhart has altered the locomotives running on the South-Eastern Railway in Russia to fit them for firing with petroleum refuse. The oil is injected as spray by steam jets into the fire-box, drawing in air at the same time. The combustion is complete, without smoke, soot, or any deposit in the tubes or furnace. Loss of heat due to the frequent opening of the furnace doors for stoking coal fires is avoided by the use of liquid fuel. The results obtained in regular practice show that 55 tons of petroleum refuse can do the work of 100 tons of coal in six-wheeled engines; that is, a reduction of 45 per cent. in weight of fuel, whilst in larger engines the saving already attained is 50 per cent. in weight as compared with anthracite.

It is thus evident that liquid fuel can do fully twice as much work as coal, and is the more desirable fuel in localities where its price is not prohibitive as compared with that of coal.

Common refined petroleum is used as fuel by the Priestman oil engine, whilst the lighter spirit drives the *Zephyr* launch. The liquid petroleum is gasified before being admitted to the cylinder of the ordinary engine, and oil gas has fully twice the heating power of ordinary coal gas.

## HEAT VALUE OF GASEOUS FUEL.

From the results in Table I. (p. 334) we can find the total heat energy evolved in the complete burning and subsequent cooling of 1 cubic foot of each gas used as fuel in the cylinder of the internal combustion engine.

We know that 1 gramme of hydrogen occupies 11·1636 litres at 0° C. and 760 m.m., and to reduce this to cubic feet per pound we are given that 1 cubic ft. is 28·316 litres, and 1 lb. equals 453·593 grammes. Now the heat of combustion of $H_2$ is 68,360 gramme-degree units per 22·3272 litres, that is, per 2 grammes of hydrogen, or per $\frac{22\cdot3272}{28\cdot316}$ cubic foot. This gives $\frac{68,360}{453\cdot593} \times \frac{28\cdot316}{22\cdot3272}$ pound-degree units per c. ft., $= 68,360 \times \cdot002796$, that is, 191·13 heat units per cubic foot of hydrogen.

In this way, multiplying the corresponding heat values by ·002796, we obtain the quantity of heat, in pound-degree Centigrade heat units, given out by the complete combustion of 1 cubic ft. of every gas in the engine cylinder.

TABLE II.—HEATS OF COMBUSTION IN OXYGEN.

| SUBSTANCE. | Products of Combustion cooled to 18° C. | 1 gramme-molecule in gramme-degree C. units. | 1 lb. of substance in lb. deg. C. units. | 1 lb. of substance in lb. deg. F. units. | 1 cubic foot of substance in lb. deg. C. units. |
|---|---|---|---|---|---|
| Hydrogen .. $H_2$ | $H_2O$ | 68,360 | 34,180 | 61,524 | 191·13 |
| Carbon .. .. C | $CO_2$ | 96,960 | 8,080 | 14,544 | .. |
| Carbonic oxide CO | $2CO_2$ | 67,960 | 2,427 | 4,368 | 190·02 |
| Marsh gas .. $CH_4$ | $CO_2 + 2H_2O$ | 209,000 | 13,063 | 23,513 | 584·36 |
| Olefiant gas .. $C_2H_4$ | $2CO_2 + 2H_2O$ | 333,350 | 11,905 | 21,429 | 932·05 |
| Acetylene .. $C_2H_2$ | $2CO_2 + H_2O$ | 310,450 | 11,940 | 21,492 | 868·02 |
| Ethane .. .. $C_2H_6$ | $2CO_2 + 3H_2O$ | 370,440 | 12,348 | 22,226 | 1035·70 |
| Tetrylene .. $C_4H_8$ | $4CO_2 + 4H_2O$ | 608,730 | 10,870 | 19,566 | 1702·00 |
| Benzene .. $C_6H_6$ | $6CO_2 + 3H_2O$ | 787,950 | 10,100 | 18,180 | 2203·10 |

Although we have much information about ordinary coal gas, yet the amount of heat generated by the combustion of 1 cubic ft. of this gas in air or oxygen has not been found directly. However, by taking the sum of the heats of combustion of each constituent gas separately, we can estimate the maximum amount of heat that can be obtained by the complete combustion of 1 cubic ft. of the coal gas. The mechanical equivalent of this heat gives us in foot-pounds the total energy obtainable from the combustion and subsequent cooling of 1 cubic ft. of the gas.

To get all this energy out of the gaseous fuel, it would be necessary to condense all the water formed, and cool it, as well as the other products of combustion, down to about 18° C. In this way the latent heat of the steam, formed by burning the hydrogen contained in all the hydrocarbons, would be developed and utilised as in modern condensing steam engines. Hitherto this has not been attained by any method devised for working internal combustion engines. However, in comparing their performance with steam engines, we must consider the consumption of coal or other fuel under the same conditions in both.

The **heat of combination** *at* 200° C. (the temperature of the charge before it is fired in some gas engines) may be calculated from that given out when the products are cooled to 18° C. Consider, for example, the case of hydrogen combining with oxygen at 200° C. We have, according to Julius Thomsen, 68,360 heat units evolved by the complete combination of 2 lb. of H with 16 lb. of oxygen, both at 18° C., when the $H_2O$ formed is cooled to 18° C. To this we must add the quantity of heat (*a*) required to raise the temperature of the initial system, $H_2$ and O, from 18° to 200° C.; and deduct from the sum the heat (*b*) required to raise the temperature of the final system, $H_2O$, through the same range of temperature.* We must know the average specific heats of hydrogen, oxygen, and steam for this range. (See p. 299.)

To calculate (*a*); 1st, the heat required to raise the 2 lb. of H is equal to mass × specific heat × range of temperature, in other words, $2 \times 3{\cdot}409 \times (200 - 18) = 1240$ units.

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* We are given that the energy of the system ($H_2$ and O) at 0° C. = energy of the system $H_2O$ at 0° C. + 68,497.

Now the energy of the system ($H_2$ and O) at 200° C. = energy of $H_2$ and O at 0° C. + $200\left(2 \times \text{specific heat of H} + 16 \times \text{specific heat of O}\right)$;

so that, energy of $H_2$ and O at 200° C. = energy of $H_2O$ at 0° C. + 68,497 + $200\left(2 \times 3{\cdot}409 + 16 \times {\cdot}2175\right) = a\ (\text{say})$

Again, the energy of $H_2O$ vapour at 200° C. = energy of $H_2O$ at 0° C. + $18\left(100 \times \text{specific heat of water} + 536 + 100 \times \text{specific heat of steam}\right) = b$.

Hence, the heat of formation of $H_2O$ vapour at 200° C., from $H_2$ and O at same temperature, is $a - b = 58{,}244$ heat units.

Next, for the 16 lb. of O the heat needed is

$$16 \times {\cdot}2175 \times (200 - 18) = 633 \text{ units.}$$

Thus *a* is 1240 + 633 = 1873.

The quantity of heat *b* may be taken in three parts: first, that required to heat the 18 lb. of liquid water from 18° to 100° C., which equals 18 × (100 − 18) = 1476 units; second, the latent heat of 18 lb. of steam = 536 × 18 = 9648 units; and third, the heat expended in raising the 18 lb. of steam from 100° to 200° C., which is 18 × 100 × ·4805 = 865 units. These together make (*b*) 11,989 units.

Hence the heat of formation of 18 lb. of $H_2O$ vapour at 200° C. from 2 lb. of H and 16 lb. of O at the same temperature, is 68,360 + 1873 − 11,989, that is, 58,244 heat units.

The heat evolved in the combination of hydrogen and oxygen continually diminishes as the temperature rises. This is partly due to the heat spent in the work of molecular separation without decomposition, causing an apparent increase of the specific heat of gases at high temperatures; and partly to the heat absorbed in chemical decomposition of the steam originally formed. When decomposition takes place at high temperatures, in such a way that lowering of temperature causes recombination, it is called *dissociation* (see page 445). The amount of dissociation depends on the temperature and pressure, and for every temperature there will be a definite proportion between the amounts of steam and the free gases, oxygen and hydrogen, present. Lowering the temperature produces recombination of the free H and O, with evolution of heat; and raising the temperature causes more chemical decomposition, heat being absorbed thereby.

Experiment shows that, as in the case of water, the heat of combustion of CO to form $CO_2$ diminishes as the temperature rises. Besides, it would appear that when $H_2O$ and CO are enclosed in the same vessel at very high temperatures, the carbon tends to completely decompose the steam.

Consequently, it will be found difficult to calculate exactly the available heat given out by the combustion of a gas under the conditions that obtain in the cylinder of the internal combustion engine. The only safe guide seems to be the **observed pressure,** which enables us to estimate the temperature reached as well as any variation in the gaseous contents of the cylinder throughout a complete cycle of the engine.

# CHAPTER XIII.

## THE WORKING FLUID.

### GASEOUS FUEL.

GAS fuel has many advantages over coal or other solid fuel. It is easy to insure thorough combustion of gas without introducing excess of air. The rate of combustion of gas is under complete control, and can be kept constant or varied at will; also, higher temperatures are obtained than with solid fuel, and a greater proportion of the heat evolved can be utilised. We have already seen that with solid fuel it is necessary to introduce fully twice the quantity of air chemically required to insure complete combustion. This means extra waste of heat to produce chimney draught, accompanied by withdrawal of heat from the fire, and loss by the escape of the partially burned carbon products, as well as by radiation from the solid residue. Besides, gas can be conveyed through pipes to any place and there manipulated and distributed with great ease. Add to these advantages the great economy in expense with natural gas or cheap fuel gas specially prepared.

On the other hand, for many purposes, more heat can be produced by the *direct combustion* of the carbon than by converting it into gas before using it as a fuel. This is obvious when we bear in mind that it is impossible to create energy by any round-about process, and that there is necessarily some loss in all methods of gasifying fuel. At the same time, *a saving of fuel may be effected by the combination of gas-producer and the internal combustion engine, in place of the boiler and steam engine.*

Gaseous fuels may be considered under the following heads :—

1. NATURAL GAS.
2. GAS FROM COAL, COKE, WOOD, AND PEAT.
3. OIL-GAS, obtained by distillation of petroleum, intermediate oils from shale, and from other oils or fats.
4. CARBURETTED AIR.

## NATURAL GAS.

Inflammable gases issue from fissures in the earth in numerous localities. *Marsh gas*, the main constituent of NATURAL GAS, may be disengaged in any stagnant pool by stirring the mud with a stick. It is known to the coal miner as *fire-damp*. In the vicinity of Baku, along the Caspian Sea, a hole need only be dug a few feet deep to have an abundant supply of gas for light and heat. The Chinese convey natural gas from deep wells by bamboo pipes, and have thus used it for centuries. In America, gas springs were known to the earliest settlers. At present the most important gas-districts are in the States of Pennsylvania, Ohio, and New York, and the gas comes from the Palæozoic strata. Marsh gas, formed by the decomposition of organic matter in the mud of shallow seas of the Devonian period, and afterwards subjected to great pressure and the internal heat of the earth, shoots forth with very great force whenever it finds vent by an artificial boring or natural fissure. In Pennsylvania there was at one time extravagant waste of this natural gas, but within recent years it is being largely used for light and fuel in manufacturing industries, as well as in dwellings in the vicinity of Pittsburgh, where the supply is very abundant.

The chemical analyses of natural gas from various parts of the world, tabulated on next page,* show that it consists mainly of marsh gas, traces of other hydrocarbons, free hydrogen, with the diluent gases carbonic acid and nitrogen.

* See *Report to American Society of Mechanical Engineers*, May 21, 1884.

ANALYSES OF NATURAL GAS.

| CONSTITUENTS. | From Marsh Ground. | Blower in Coal Mine, Wales. | Occluded in Cannel Coal, Wigan. | Baku, Caspian Sea. | Olean, New York. | Pittsburgh. | Leechburgh. | Harvey Well, Butler Co., Pa. | Burns's Well, Butler Co., Pa. | Creighton. | Roge r's Gulch, Wirt Co., West Virginia. | Petrolia, Canada. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydrogen .. .. .. H | .. | .. | .. | 0·98 | .. | 22·0 | 4·79 | 13·50 | 6·10 | .. | Chiefly marsh gas, with some carbonic acid and nitrogen. | Chiefly marsh gas, with ethane and some carbonic acid. |
| Marsh gas .. .. $CH_4$ | 47·37 | 95·42 | 80·69 | 93·99 | 96·50 | 67·0 | 89·65 | 80·11 | 75·44 | 96·34 | | |
| Ethane .. .. .. $C_2H_6$ | .. | .. | 4·75 | .. | .. | 5·0 | 4·39 | 5·72 | 18·12 | .. | | |
| Heavy hydrocarbons .. | .. | .. | .. | 3·26 | 1·00 | 1·0 | 0·56 | .. | .. | trace | | |
| Carbonic oxide .. CO | .. | .. | .. | .. | 0·50 | 0·6 | 0·26 | trace | trace | .. | | |
| Carbonic acid .. .. $CO_2$ | 3·10 | 0·60 | 6·44 | 2·18 | .. | 0·6 | 0·35 | 0·66 | 0·34 | 3·64 | | |
| Nitrogen .. .. .. N | 49·39 | 3·98 | 8·12 | 0·49 | .. | 3·0 | .. | .. | .. | .. | | |
| Oxygen .. .. .. O | 0·17 | .. | .. | .. | 2·00 | 0·8 | .. | .. | .. | .. | | |
| Maximum heat evolved in burning 1 cubic foot (lb. degree centigrade units) | .. | .. | .. | 576·22 | .. | 495·81 | 584·21 | 552·90 | 639·73 | | | |

The composition of gas from the same well is found to vary, and specimens from different localities do not always contain the same constituents.

To **calculate the maximum heating power** of one cubic foot of natural gas, take for example the gas from the vicinity of Pittsburgh, of which the average composition, according to analyses by Mr. S. A. Ford, is given in above table.

Now we know that 1 cubic foot of hydrogen gives out on complete combustion 191·13 units of heat, therefore, 0·22 cubic foot of hydrogen will give 0·22 x 191·13, or 42·05 units of heat.

Calculating in this way the different quantities of heat evolved by the other constituents separately, and adding all together, we see that the greatest amount of heat evolved by burning 1 cubic foot of Pittsburgh natural gas is 495·82 units.

COMPOSITION AND HEAT VALUE OF PITTSBURGH NATURAL GAS.

| CONSTITUENTS. | Volume of Constituent in 1 cubic foot of Natural Gas. | Heat Value per cubic foot of Constituent. | Heat Value of given amount in Natural Gas (lb. degree Centigrade - units.) |
|---|---|---|---|
| Hydrogen .. .. .. .. .. $H$ | 0·22 | 191·13 | 42·05 |
| Marsh gas .. .. .. .. .. $CH_4$ | 0·67 | 584·36 | 391·52 |
| Ethane .. .. .. .. .. .. $C_2H_6$ | 0·05 | 1035·7 | 51·79 |
| Heavy hydrocarbons .. .. .. | 0·01 | 932·05 | 9·32 |
| Carbonic oxide .. .. .. $CO$ | 0·006 | 190·02 | 1·14 |
| Carbonic acid .. .. .. $CO_2$ | 0·006 | | |
| Nitrogon .. .. .. .. .. $N$ | 0·030 | | |
| Oxygen .. .. .. .. .. $O$ | 0·008 | | |
| Total .. .. .. .. .. | 1·000 | .. | 495·82 |

All this heat is not available, part of it is used in raising the temperature of the non-combustible gases, as well as of the products of combustion. We may deduct about 10 per cent. from the total and take 1000 cubic feet of this natural gas as equivalent in heating power to 55 lb. of bituminous coal, which develop 55 × 8000, or 440,000 heat units.

### GAS FROM COAL, COKE, AND WOOD.

The following devices have been used to produce gas from coal and coke :—

1. Closed retorts heated externally, to distil hydrocarbons from coal out of contact with air, and yield ordinary **coal gas.**

2. Gas generators or Producers, in which coal is converted into gas by combustion with air ; sometimes steam is added to the air supply, and the hydrocarbons are distilled as **producer gas.**

3. Producers in which steam is decomposed by incandescent anthracite or coke, and **water gas** formed.

COAL GAS is obtained by the destructive distillation of coal. The coal is placed in closed retorts of fire-clay or cast iron, which are kept at regulated high temperatures. The crude gas, going off from the retorts, is passed through a hydraulic main and then through a series of cooling pipes called atmospheric condensers, in which the gas deposits a large quantity of tar and ammonia products. In the next stage of this process of purification, the gas passes through scrubbers, that is, towers filled with coke moistened with ammonia-water spray, which absorbs some of the sulphuretted hydrogen ($H_2S$) and carbon disulphide ($CS_2$). The remainder of these impurities, together with carbonic acid ($CO_2$), are absorbed by layers of slaked lime, or better still by a mixture of slaked lime with sulphate of iron, finely divided and made porous by sawdust, over which the gas passes before it is stored in the gas-holders and called coal gas.

The quality and quantity of gas formed varies very much with the nature and composition of the coal used, as well as with the temperature at which distillation is carried on, and the time it is allowed to continue.

Dr. Henry was the first to determine accurately the composition of the mixture of gases which we call coal gas. The influence of temperature during the distillation is shown by his analyses of specimens of the gas coming off at various stages. Wigan cannel coal was used. One cubic foot of gas contained the following fractions of a cubic foot of its constituents :—

| Time of Collection. | Specific Gravity. | Hydrogen, H. | Marsh Gas, $CH_4$. | Carbonic Oxide, CO. | Heavy Hydro-carbons. | Nitrogen, N. |
|---|---|---|---|---|---|---|
| 1st hour .. | ·650 | 0 | ·825 | ·032 | ·13 | ·013 |
| | ·620 | ·088 | ·720 | ·019 | ·12 | ·053 |
| | ·630 | ·160 | ·58 | ·123 | ·12 | ·017 |
| 5th hour .. | ·500 | ·213 | ·56 | ·110 | ·07 | ·047 |
| 13th hour . | ·345 | ·600 | ·20 | ·100 | 0 | ·100 |

It will be observed that, as the distillation proceeds, the specific gravity of the issuing gases decreases with the quantity of marsh gas and hydrocarbons, whilst the hydrogen rapidly increases.

These results are in accord with similar experiments* made by Mr. Lewis T. Wright. His samples were taken off clay retorts distilling Newcastle coal in the ordinary process of gas making, but under slight pressure, in order to prevent air entering the retort. The coal required six hours for its proper distillation.

| CONSTITUENTS OF COAL GAS. | Time after Commencement of Distillation. | | | |
|---|---|---|---|---|
| | 10 minutes. | 1 hour 30 minutes. | 3 hours 25 minutes. | 5 hours 35 minutes. |
| Hydrogen.. .. .. .. .. H | ·2010 | ·3833 | ·5268 | ·6712 |
| Marsh gas .. .. .. .. $CH_4$ | ·5738 | ·4403 | ·3354 | ·2258 |
| Carbonic oxide .. .. CO | ·0619 | ·0568 | ·0621 | ·0612 |
| Heavy hydrocarbons .. .. | ·1062 | ·0598 | ·0304 | ·0179 |
| Nitrogen .. .. .. N | ·0220 | ·0247 | ·0255 | ·0078 |
| Carbonic acid .. .. .. $CO_2$ | ·0221 | ·0209 | ·0149 | ·0150 |
| Sulphuretted hydrogen .. $H_2S$ | ·0130 | ·0142 | ·0049 | ·0011 |

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* *Journal of Chemical Society*, No. cclvi., 1884.

The quantity of gas produced from a given sample of coal increases with the temperature of distillation and the time it is continued.

The following is the usual yield from different kinds of coal:—

| NAME OF COAL. | Cubic Feet of Gas yielded per Ton of Coal. | Weight of Gas in Pounds per Ton of Coal. | Cubic Feet of Gas from 1 lb. of Coal. | Weight of Gas in Pounds per lb. of Coal. | Number of Cubic Feet in 1 lb. of Gas at ordinary Pressure and Temperature. |
|---|---|---|---|---|---|
| Newcastle .. . .. | 11,492 | 398 | 5·130 | ·1776 | 28·87 |
| ,, .. .. .. | 11,336 | 362 | 5·060 | ·1616 | 31·32 |
| Wigan .. .. .. | 9,500 | 357 | 4·241 | ·1594 | 26·61 |
| ,, .. .. .. | 9,408 | 344 | 4·200 | ·1536 | 27·35 |
| Scotch Parrot .. .. | 9,500 | 466 | 4·241 | ·2080 | 20·39 |
| Lesmahago cannel .. | 11,312 | 638 | 5·050 | ·2848 | 17·73 |
| Boghead ,, .. | 15,000 | 866 | 6·696 | ·3866 | 17·32 |
| Incehall ,, .. | 11,400 | 461 | 5·090 | ·2058 | 24·73 |
| Derbyshire .. .. | 9,400 | 308 | 4·197 | ·1375 | 30·52 |
| ,, .. .. | 7,166 | 256 | 3·200 | ·1143 | 27·99 |
| Neath, South Wales | 11,200 | 401 | 5·000 | ·1790 | 27·93 |
| West Bromwich .. | 6,500 | 226 | 2·902 | ·1009 | 28·76 |
| Staffordshire .. .. | 10,467 | 302 | 4·673 | ·1348 | 34·66 |

One ton of coal yields from 6500 to 15,000 cubic feet of coal gas, having a specific gravity of from 0·37 to 0·75 relatively to common air. We may take it then, that, on an average, 1 ton of coal yields about 10,000 cubic feet of gas having a specific gravity of 0·6; or **1 lb. of coal yields about 4·5 cubic feet of ordinary coal gas.**

Table I. shows the composition of coal gas in various localities, as given by F. Chandler.*

Table II. is taken from numerous analyses of gas supplied for lighting purposes in Great Britain, made by Dr. P. F. Frankland.†

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* *American Chemist*, vi. 285.

† *Journal of the Chemical Society*, No. cclix., 1884.

### Table I.—Coal Gas.

| | Heidelberg. | Bonn. | Chemnitz. | London. | | Manchester Cannel Gas. (Bunsen & Roscoe.) |
|---|---|---|---|---|---|---|
| | | | | Ordinary Coal Gas. | Cannel Gas. | |
| Hydrogen .. $H$ | ·4400 | ·3980 | ·5129 | ·4600 | ·2770 | ·4558 |
| Marsh gas .. $CH_4$ | ·3840 | ·4312 | ·3645 | ·3950 | ·5000 | ·3490 |
| Carbonic oxide $CO$ | ·0573 | ·0466 | ·0445 | ·0750 | ·0680 | ·0664 |
| Heavy hydrocarbons | ·0727 | ·0475 | ·0491 | ·0380 | ·1300 | ·0646 |
| Nitrogen .. $N$ | ·0423 | ·0465 | ·0141 | ·0050 | ·0040 | ·0246 |
| Carbonic acid $CO_2$ | ·0037 | ·0302 | ·0108 | .. | ·0010 | ·0367 |
| Water vapour $H_2O$ | .. | .. | .. | ·0200 | ·0100 | .. |
| | | | | | | $H_2S$ = ·0029 |

### Table II.—Composition of Coal and Cannel Gases, 1882–4.

| Town. | Coal used. | Hydrogen, $H$. | Marsh Gas, $CH_4$. | Carbonic Oxide, $CO$. | Heavy Hydrocarbon. | Nitrogen, $N$. | Carbonic Acid, $CO_2$. | Oxygen, $O_2$. |
|---|---|---|---|---|---|---|---|---|
| Edinburgh .. .. | cannel | ·3324 | ·4293 | ·0661 | ·1223 | ·0364 | ·0035 | ·0100 |
| Glasgow .... .. | ,, | ·3918 | ·4026 | ·0714 | ·1000 | ·0307 | ·0029 | ·0006 |
| St. Andrews .. .. | ,, | ·3663 | ·4213 | ·0516 | ·1004 | ·0283 | ·0273 | ·0048 |
| Liverpool .. .. | ,, | ·3644 | ·4428 | ·0339 | ·0790 | ·0610 | ·0170 | ·0019 |
| Preston .. .. .. | ,, | ·4395 | ·3933 | ·0462 | ·0622 | ·0479 | ·0084 | ·0025 |
| Leeds .. .. .. | ,, | ·4023 | ·4274 | ·0502 | ·0728 | ·0432 | ·0034 | ·0007 |
| Sheffield .. .. | ,, | ·4305 | ·4305 | ·0472 | ·0628 | ·0256 | ·0024 | ·0010 |
| Nottingham .. .. | coal | ·4552 | ·3966 | ·0563 | ·0563 | ·0251 | ·0081 | ·0024 |
| Birmingham .. .. | ,, | ·4023 | ·3900 | ·0405 | ·0476 | ·1010 | ·0150 | ·0036 |
| Bristol .. .. .. | ,, | ·4457 | ·4070 | ·0477 | ·0458 | ·0511 | none | ·0027 |
| London Gas Light and Coke Co. .. | ,, | ·4799 | ·3764 | ·0375 | ·0441 | ·0595 | none | ·0026 |
| South Metropolitan .. .. | ,, | ·5314 | ·3655 | ·0411 | ·0292 | ·0319 | ·0009 | none |
| Redhill .. .. .. | ,, | ·4818 | ·3941 | ·0341 | ·0440 | ·0337 | ·0074 | ·0049 |
| Gloucester .. .. | ,, | ·4889 | ·3825 | ·0464 | ·0495 | ·0273 | ·0003 | ·0051 |
| Newcastle-on-Tyne | ,, | ·5050 | ·3671 | ·0337 | ·0362 | ·0529 | ·0028 | ·0023 |
| Newcastle, Staffordshire .. .. .. | ,, | ·4631 | ·3901 | ·0374 | ·0453 | ·0622 | ·0008 | ·0011 |
| Brighton .. .. | ,, | ·5162 | ·3815 | ·0414 | ·0376 | ·0207 | ·0003 | ·0023 |
| Southampton .. | , | ·5359 | ·3674 | ·0359 | ·0309 | ·0253 | ·0007 | ·0039 |
| Ipswich .. .. .. | ,, | ·4326 | ·3873 | ·0246 | ·0453 | ·1084 | ·0006 | ·0012 |
| Norwich .. .. | ,, | ·5379 | ·3611 | ·0340 | ·0326 | ·0303 | ·0027 | ·0014 |

The excess of nitrogen in these specimens of coal gas must be derived from the atmosphere, and is supposed to be largely due to the employment of fire-clay instead of the old iron retorts. Owing to the porous nature of the fire-clay retorts, nitrogen from the air may be introduced into the crude coal-gas ; part of this goes to form ammonia and tar, but as yet it is not clear what becomes of the rest.* Recently special attention has been directed to the nitrogen in coal, and to the ammonia and tar produced by the distillation. It appears that the nitrogen in coal does not exceed 2 per cent. and the residual coke contains from 40 to 66 per cent. of this. Coal-gas manufacturers are daily becoming more alive to the importance of the by-products, such as tar and ammonia, and to the production of coke and a cheap gas for heating purposes.

The above tables show that the composition of coal gas varies considerably, but, happily for our purposes, whatever be the composition taken, we find nearly the same quantity of heat generated by the combustion of one pound of coal gas in the engine cylinder and nearly the same properties in the products of combustion.

It will be observed that, as the presence of heavy hydrocarbons is what mainly gives coal-gas its illuminating power, and as these are always in such small quantities that more or less of them produce practically no effect in the heating power, we need not, for gas engine purposes, make the distinctions which are usual with gas engineers.

Taking the composition of ordinary London coal gas as given above, and assuming, as we have a fairly good right to do, that the heavy hydrocarbons are olefiant gas ($C_2H_4$) and tetrylene ($C_4H_8$), in the proportions of 2 to 1, we are in a position to consider the chemical changes during the combustion of coal gas.

We shall first determine the **amount of oxygen**

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* See paper on the *Composition and Destructive Distillation of Coal*, by Professor W. Foster, in *Minutes of Proceedings of the Institution of Civil Engineers*, vol. lxxvii., part iii., 1883-4.

**required** for the complete burning of each constituent of one cubic foot of very good London coal gas having the composition given above in Table I.

When the constituent gases are separately burnt the interactions that occur are expressed by the chemical equations :—

(1) $$2H_2 + O_2 = 2H_2O\,;$$

that is, 2 c. ft. of hydrogen + 1 c. ft. of oxygen give 2 c. ft. of water vapour ;
hence, ·46 ,, ,, + 0·23 ,, ,, give ·46 ,, ,,

(2) $$CH_4 + 2O_2 = CO_2 + 2H_2O\,;$$

that is, 1 c. ft. marsh gas + 2 ft. oxygen give 1 ft. carbonic acid + 2 ft. water vapour ;
hence, ·395 ,, ,, + ·79 ,, give ·395 ,, ,, + ·79 ,, ,,

(3) $$2CO + O_2 = 2CO_2\,;$$

or, 2 c. ft. carbonic oxide + 1 ft. oxygen give 2 ft. carbonic acid gas,
or, ·075 ,, ,, + ·0375 ,, give ·075 ,, ,,

(4) $$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O\,;$$

or, 1 c. ft. olefiant gas + 3 ft. oxygen give 2 ft. carbonic acid + 2 ft. water vapour ;
or, ·0253 ,, ,, + ·0759 ,, give ·0506 ,, ,, + ·0506 ,, ,,

(5) $$C_4H_8 + 6O_2 = 4CO_2 + 4H_2O\,;$$

or, 1 c. ft. tetrylene + 6 ft. oxygen give 4 ft. carbonic acid + 4 ft. water vapour ;
or, ·0127 ,, + ·0762 ,, give ·0508 ,, ,, + ·0508 ,, ,,

The nitrogen may form with oxygen, nitrous acid, or some of the lower oxides of nitrogen, but these, as well as the water vapour, are decomposed at the high temperatures produced by the combustion. Any sulphur present is ultimately converted into sulphuric acid.

The maximum **heat evolved** by the complete combustion of 1 cubic foot of the coal gas and subsequent cooling of the products to 18° C. is easily calculated by adding together the quantities of heats given out by the different constituents (see p. 355). This includes the latent heat of the steam formed by the combustion of the hydrogen in all the hydrocarbons, which is clearly not available until the steam is condensed to liquid water, and therefore cannot be realised in the ordinary internal combustion engine. The total heat evolved in the complete combustion of 1 cubic foot of coal gas is thus estimated to be 378·19 units.

Arranging the figures in a table, we get some idea of the nature of the working fluid in the cylinder of a gas engine.

TABLE III.—COMBUSTION OF COAL GAS.

| CONSTITUENTS. | Volume of Constituent in 1 Cubic Foot of Coal Gas. | Heat Evolved (lb. degree C.) | | Oxygen required. | | Volume of Products of Combustion. | |
|---|---|---|---|---|---|---|---|
| | | By 1 Cubic Foot of each Gas. | By Amount of each Present. | By 1 Cubic Foot of each Gas. | By Given Amount of each. | Per Cubic Foot of each. | Per Given Amount of each. |
| Hydrogen .. $H$ | ·4600 | 191·13 | 87·92 | 0·5 | 0·2300 | 1 | 0·460 |
| Marsh gas .. $CH_4$ | ·3950 | 584·36 | 230·82 | 2 | 0·7900 | 3 | 1·185 |
| Olefiant gas $C_2H_4$ | ·0253 | 932·05 | 23·58 | 3 | 0·0759 | 4 | 0·1012 |
| Tetrylene .. $C_4H_8$ | ·0127 | 1702·00 | 21·62 | 6 | 0·0762 | 8 | 0·1016 |
| Carbonic acid $CO$ | ·0750 | 190·02 | 14·25 | 0·5 | 0·0375 | 1 | 0·075 |
| Nitrogen .. $N$ | ·0050 | .. | .. | .. | .. | .. | 0·005 |
| Water vapour $H_2O$ | ·0200 | .. | .. | .. | .. | .. | 0·020 |
| | .. | .. | 378·19 | .. | 1·2096 | .. | 1·9478 |

## Products in the Gas Engine Cylinder.

We see that one cubic foot of coal gas requires 1·2096 cubic feet of oxygen for complete combustion, and the products consist of

1·3714 cubic feet of water vapour,
0·5714 „ „ carbonic acid,
0·0050 „ „ nitrogen.

Now, as it is air we admit into gas engines for the combustion of the gas, we must remember that for every 21 cubic feet of oxygen admitted we also have 79 cubic feet of nitrogen; so that, instead of saying that 1·2096 cubic feet of oxygen are necessary for the combustion of 1 cubic foot of coal gas, we must say that $1 \cdot 2096 \times \frac{100}{21}$, or 5·760 cubic feet of air, are necessary, and this contains 4·5504 cubic feet of nitrogen, in addition to the necessary oxygen. A mixture, then, of 1 cubic foot of coal gas and 5·760 cubic feet of air becomes, after complete combustion,

| | | | |
|---|---|---|---|
| 1·3714 | cubic feet of | | water vapour, |
| 0·5714 | „ | „ | carbonic acid, |
| 0·0050 | „ | „ | original nitrogen, |
| 4·5504 | „ | „ | diluting nitrogen; |

that is, a mixture of 6·760 feet of air and coal gas becomes, after complete combustion, 6·4982 feet, consisting of carbonic acid, water vapour, and nitrogen, reduced to the same pressure and temperature without condensation of water vapour.

Now, as there is always an excess of air, and as the mixture before combustion has added to it nearly 6 feet of the products of previous combustions in the gas engine cylinder, we have something like 13·3 cubic feet before combustion, becoming 13·0382 cubic feet after combustion, at equivalent pressures and temperatures. The contraction is only about 2 per cent. We shall not therefore err largely, in so far as mechanical actions are concerned, if we regard the working substance in the gas engine as a fluid which, however it may receive heat, obeys approximately the characteristic law,

$$\frac{pv}{T} \text{ constant,}$$

where $p$ stands for pressure, $v$ volume, and T the absolute temperature. That is, we may speak of it as a perfect gas which receives heat from without, neglecting the fact that it is really its own molecular energy which appears as heat.

It is also approximately true that the ratio of the specific heats of the fluid is unchanged by combustion taking place. If we could be sure that the ratio of the specific heat at constant pressure to the specific heat at constant volume, that is, $\gamma$, or $C_p \div C_v$, remained constant for a mixture of coal gas and air, as it does for air itself, viz. 1·408 always, we should be quite confident in making our calculations for the changes the working fluid undergoes in the cylinder of the internal combustion engine. The specific heats of the substances mixed together are different from one another, as well as from the specific heats of the products of combustion. We want to find the specific heat of a mixture of 1 cubic foot of coal gas, 5·76 cubic feet of air, and 4·5 cubic feet of products from previous combustions, before and after explosion takes place, as in the cylinder of an Otto gas engine. Use the specific heats of the constituents in the cold state, as given in page 299. We have also seen that the mixture behaves like a perfect gas, $\frac{pv}{T}$ remains constant, hence we can find the weight of each gas.

*Multiply the weight of each constituent gas by its specific heat at constant pressure, also at constant volume, and we find the amounts of heat required to raise each through* 1° *C. at constant pressure and at constant volume.*

The sum of all such products, weight × $C_p$, divided by the sum of all products, weight × $C_v$, gives the ratio $\gamma = 1·385$ for the mixture before combustion. By similar calculation $\gamma = 1·367$ for the burnt products.

The discrepancy here is small, but unfortunately we shall be using the excess of these numbers above unity, that is, $\gamma - 1$ or ·385 and ·367, where the difference becomes proportionately greater. We also know that the specific heats vary with the temperature, but, seeing there is no great change due to combustion, we may, for many practical purposes, assume that the ratio of the specific heats remains the same at all temperatures.

Professor Perry tabulates the calculations* for the above results as follows :—

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* See paper on "The Gas Engine Indicator Diagram," by Professors W. E. Ayrton, F.R.S., and John Perry, M.E., *Phil. Mag.*, July 1884.

TABLE IV.—COAL GAS BEFORE COMBUSTION.

| CONSTITUENT. | Amount in Fluid. | Specific Heat at Constant Pressure per Unit Volume. | Specific Heat at Constant Volume per Unit Volume. | | |
|---|---|---|---|---|---|
| | Cubic feet. $q$. | $C_p$. | $C_v$. | $qC_p$. | $qC_v$. |
| Hydrogen .. .. | ·46 | ·2359 | ·99 × ·168 | ·1085 | ·4554 × ·168 |
| Carbon monoxide .. | ·075 | ·237 | 1 ,, | ·0178 | ·0750 ,, |
| Marsh gas .. .. | ·395 | ·3277 | 1·54 ,, | ·1294 | ·6082 ,, |
| Olefiant gas .. .. | ·038 | ·4106 | 2·03 ,, | ·0156 | ·0771 ,, |
| Nitrogen .. .. | ·005 | ·237 | 1 ,, | ·0012 | ·0050 ,, |
| Water vapour .. | ·020 | ·2984 | 1·36 ,, | ·0060 | ·0272 ,, |
| Air .. .. .. .. .. | 5·76 | ·2374 | 1 ,, | 1·3680 | 5·760 ,, |
| Products .. .. | 4·5 | ·2581 | 1·124 ,, | 1·1614 | 5·058 ,, |
| Total .. .. | 11·253 | .. | .. | 2·8079 | 12·066 × ·168<br>= 2·027 |

$\therefore C_p = 0·2496, \quad C_v = 0·1802. \qquad \text{Ratio } \gamma = 1·385.$

TABLE V.—PRODUCTS OF COMBUSTION.

| CONSTITUENT. | Cubic feet. $q$. | $C_p$. | $C_v$. | $qC_p$. | $qC_v$. |
|---|---|---|---|---|---|
| Water vapour .. .. | 1·3714 | ·2984 | 1·36 × ·168 | 0·4092 | 1·865 × ·168 |
| Carbon dioxide .. | 0·5714 | ·3307 | 1·55 ,, | 0·1889 | 0·8855 ,, |
| Nitrogen .. .. | 4·5554 | ·2370 | 1 ,, | 1·0790 | 4·5554 ,, |
| Total .. .. | .. | .. | .. | 1·6771 | 7·3059 × ·168<br>or 1·227 |

$\therefore C_p = 0·2581, \quad C_v = 0·1889. \qquad \text{Ratio } \gamma = 1·367.$

This ratio $\gamma$ depends on the quality of the gas and the volume of air admitted.

In trials of an Otto engine, by Messrs. Morgan Brooks and J. E. Steward, under the direction of Professor Robert H. Thurston, at the Stevens Institute of Technology, Hoboken, in America (see p. 517), using coal gas, the specific heats of the products of combustion were determined from the specific heats of the component gases. Both the gas and air entering the engine were measured by meter, and found to be in the ratio 1 volume of poor gas to about 7 of air when the engine was working most economically.

Unit weight of gas burned with 12·26 parts of air gave 13·26 units by weight of a mixture having the following composition and specific heat:—

PRODUCTS OF COMBUSTION.

| CONSTITUENT. | | Amount per Unit Weight of Mixture. | Specific Heat at Constant Pressure per Unit Weight. | $C_p$ of given Amount. | Specific Heat at Constant Volume per Unit Weight. | $C_v$ of given Amount. |
|---|---|---|---|---|---|---|
| Steam .. .. | $H_2O$ | 0·131 | ·4805 | ·0629 | ·3694 | ·0484 |
| Carbonic acid .. | $CO_2$ | 0·146 | ·2169 | ·0317 | ·1714 | ·0250 |
| Nitrogen .. .. | N | 0·721 | ·2438 | ·1758 | ·1727 | ·1245 |
| Impurities .. .. .. | | 0·002 | ·4 | ·0008 | ·3 | ·0006 |
| | | 1·000 | | ·2712 | | ·1985 |

The ratio of the specific heats is found to be

$$\gamma = \frac{C_p}{C_v} = \frac{\cdot 2712}{\cdot 1985} = 1\cdot 366.$$

The excess of air present modifies these figures, since for air $C_p = \cdot 2375$ and $C_v = \cdot 1684$. The meter records show 13·68 instead of the 12·26 parts by weight of air needed for complete combustion.

Thus

$$C_p = \frac{\cdot 2712 \times 13\cdot 26 + \cdot 2375 \times 1\cdot 42}{14\cdot 68} = \cdot 268,$$

and

$$C_v = \frac{\cdot 1985 \times 13\cdot 26 + \cdot 1684 \times 1\cdot 42}{14\cdot 68} = \cdot 196,$$

hence

$$\gamma = \frac{\cdot 268}{\cdot 196} = 1\cdot 37.$$

This ratio may also be determined directly from the expansion curve of the indicator diagram. (See p. 428.)

It is necessary to know the specific heat of the mixture of burnt products or waste gases in order to be able to calculate the heat rejected by the exhaust.

## PRODUCER GAS.

We have already seen that as early as 1791, John Barber took out a patent, No. 1833, in which he proposed to use "inflammable air" for driving an engine and for metallurgical operations. The inflammable air was produced by *heating coal, wood, oil*, or any other combustible matter in a *metallic retort*, collecting and cooling the vapour in a cistern with water.

In the year 1801 Lampadius proved that the waste gases from the carbonization of wood could be used for metallurgical work.* Since then numerous **producers** have been devised and used with wood, peat, and coal, to yield gaseous fuel.

Early attempts to obtain gas consisted in keeping a retort containing fuel at a high temperature by means of external fires, steam being forced through the fuel and decomposed thereby.

The rapid deterioration of the retorts led to an alternating but cheaper method of working.

In 1852–4 Messrs. T. and W. Kirkham dispensed with the external fires previously used for heating the retorts. The fuel was first lighted in the generator or gas producer, and an air-blast passed through the fuel to raise its temperature by combustion. Then the air was shut off and steam let in, until by its decomposition the lowering of the temperature rendered another air-blast necessary. This intermittent method of working gave rise to differences in the composition of the gas, even when the greatest care was taken, it being generally found that the largest amounts of carbonic oxide were obtained towards the end of each operation.

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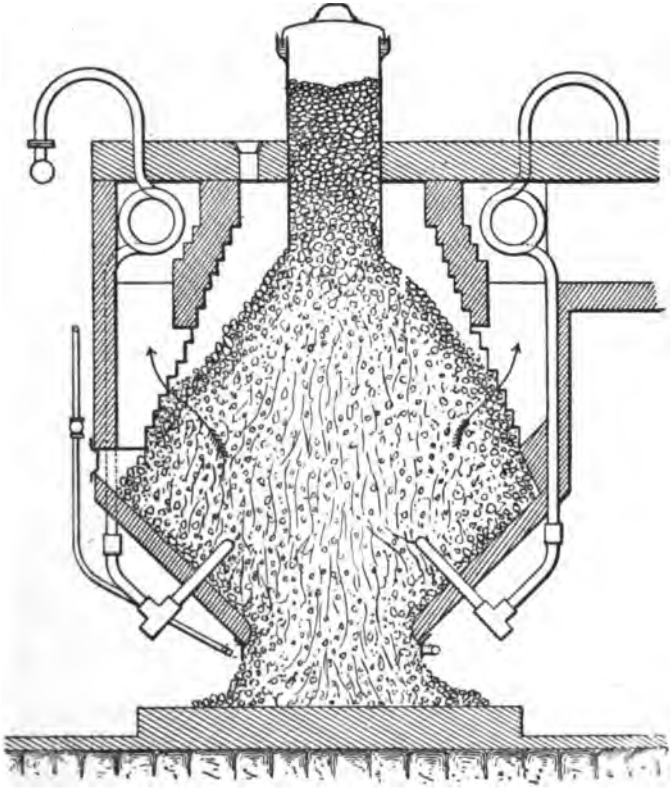
* See *Gas Producers*, by Mr. F. J. Rowan, *Minutes of Proceedings Inst. C.E.*, 1886, vol. lxxxiv. p. 2. *A Practical Treatise on Metallurgy*, by W. Crookes and E. Rohrig, vol. iii. Dr. Percy's *Metallurgy*.

The SIEMENS PRODUCER is well known in connection with his regenerative furnace. In the **old type producer,** having sloping grate with bars and open ash-pit, air with a little water vapour passes through a mass of incandescent fuel and maintains sufficient combustion of the fuel to keep up the heat. Usually the air is drawn in by a chimney-draught, but sometimes it is forced in under the bars by a steam injector. As the mixture of steam and gas is passed through the red-hot fuel, the steam ($H_2O$) is decomposed, and the oxygen

FIG. 170.



SIEMENS' NEW TYPE CIRCULAR PRODUCER.

combines with the carbon of the fuel to form carbonic acid ($CO_2$), which at a later stage is in its turn reduced to carbonic oxide (CO) and oxygen, some of which again forms $CO_2$. The ultimate result of the action of steam on incandescent carbon, forming water-gas, is

$$C + H_2O = CO + H_2.$$

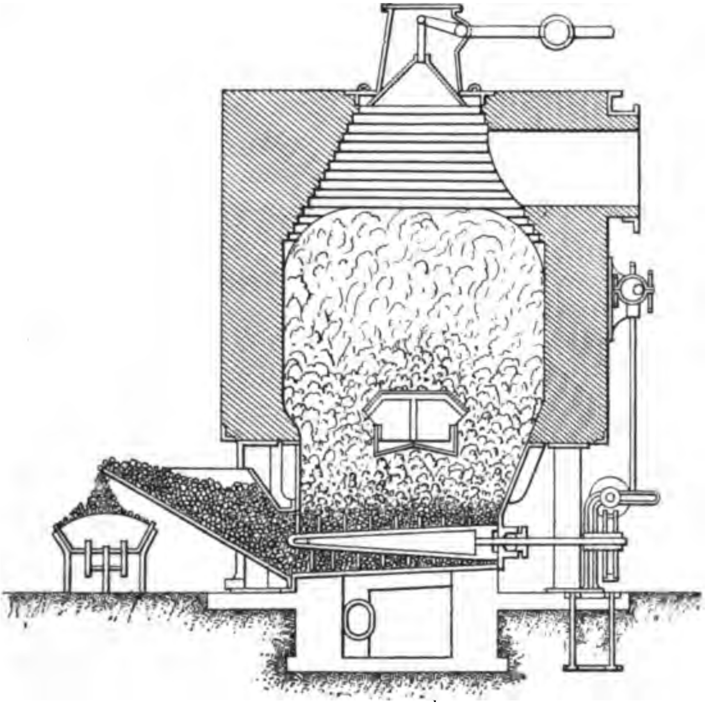
The resulting gas contains from 60 to 70 per cent. of nitrogen, and is unsuitable for use in the gas engine although successfully used with the Siemens' regenerator in metallurgical operations, and especially when the arrangement of gas producer and regenerator has the improvements which have been effected in it by certain French engineers. The incoming gas and air are heated by the outgoing waste products. The difficulty in the above process was to keep a sufficient quantity of red-hot fuel to prevent the steam passing through undecomposed, and it had to be stopped to allow the fire to burn up again.

In the **new type producer**, Fig. 170, Sir William Siemens adopted the circular form, open at the bottom and of inverted cone-shape. Steam from a small steam-pipe plays on the hot ashes at the bottom of the producer, and the steam is drawn in with the air through the fuel by the chimney-draught. With wood, peat, or fuel containing moisture, cooling tubes are used to condense the water-vapour and promote the draught. A steam jet is also shown.

The **Wilson gas producer**, Fig. 171, consists of an iron casing having brickwork lining, tapering at the top, and a closed hearth without grate bars at the bottom. The fuel is fed by a bell and hopper into the upper portion, which also acts as a retort to distil the heavier hydrocarbons. Right across the centre of the hearth runs a box with tuyeres at each side, and here, as far from the side walls as possible, a steam-jet entering by a tapered pipe draws in air on the injector principle, in the proportion of 20 parts air to 1 part by weight of steam.

The danger with high pressure blast is that air currents may pass up the side walls without entering the fuel, since the compressed gases have a tendency to take channels therein, so that a large volume of the carbonic acid is likely to escape reduction. It is, therefore, necessary to introduce the air at the centre of the producer, which must be kept well filled with fuel. The decomposition of the steam by coal at a bright red-heat, absorbs heat and so protects the iron tuyeres, and renders the clinker brittle, whilst the hydrogen and carbonic oxide formed pass upward through the fuel. The consumption of fuel is at the rate of about 25 to 30 lb. of fuel per square foot of hearth area per hour, which is double that of the Siemens' sloping grate-producers with chimney-draught.

FIG. 171.



WILSON AUTOMATIC PRODUCER.

In 1882 Wilson introduced the **Automatic Producer,** which is the first with continuous removal of the ash and clinker as well as feeding by machinery. Iron worm-screws work in troughs kept filled with *water*, which acts as a seal to the producer, *absorbs the waste heat from the ash and clinker, whilst the steam formed passes up through the fuel and is decomposed.* When *anthracite or good coke* is employed as fuel, and the gases washed to get rid of all the tarry products, the Wilson producer may be used to supply the internal combustion engine with gaseous fuel.

## DOWSON GAS.

To Mr. J. Emerson Dowson is due the improvement which has led to the practical success of cheap generator gas-making, and especially to the economical working of gas engines.*

The Dowson gas is made by forcing a mixture of steam and air through a mass of red-hot fuel, and by this means not only is the steam decomposed into its constituent gases, oxygen and hydrogen, but a sufficiently high temperature is maintained in the generator to carry on the process *continuously.*

A complete and compact set of the Dowson plant is shown in plan, elevation, and section, Figs. 172, 173, and 174.

It consists of the steam producer and superheater E, injector C, gas generator A, with waste-pipe and chimney used in starting, downpipe F conveying gas to the hydraulic box G, inlet pipe H from hydraulic box to wet-scrubber I, with water-supply *i* and spray pipes I′ inside the gas holder K (Fig. 174), dry scrubber J, outlet pipe *k* from gas-holder to left compartment of the hydraulic box G, and by gas supply main H′ to the engine, regulating valve *n* by chain N for escape of steam and air.

The **Generator** A is made of iron, lined with brick, ganister, or other refractory material, to prevent loss of heat and oxidation of the metal. The fuel introduced by the hopper A′ rests on a grate *a*, near the bottom, Fig. 174.

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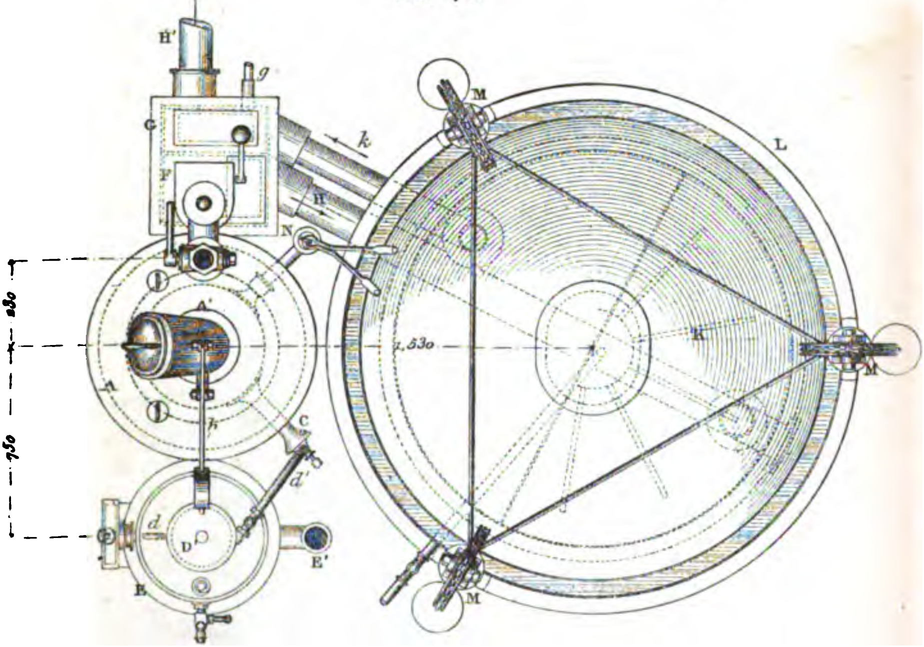
* See the following papers by Mr. J. Emerson Dowson, M. Inst. C.E., *On the Production and Use of Gas for Heating and Motive Power*, in the *Journal of the Society of Arts*, 22nd February, 1882; *Cheap Gas for Motive Power*, *Minutes of Proceedings Inst. C.E.*, vol. lxxii. part 3; *Gas Power compared with Steam Power*, ibid., vol. lxxxix. part 3; also a paper on *Gaseous Fuel*, at the Bath meeting of British Association, September 8, 1888.

Usually the **steam is produced and superheated** in a small boiler, E, with a spiral coil of iron tube *d* over the fire, but sometimes in a zig-zag coil heated by gas drawn from the gas-holder, or steam from a neighbouring boiler may be superheated in a separate coil.

A current of superheated steam passes continuously by the pipe *d'* through the injector C, which consists of a nozzle inserted in the mouth of a conical tube open to the atmosphere.

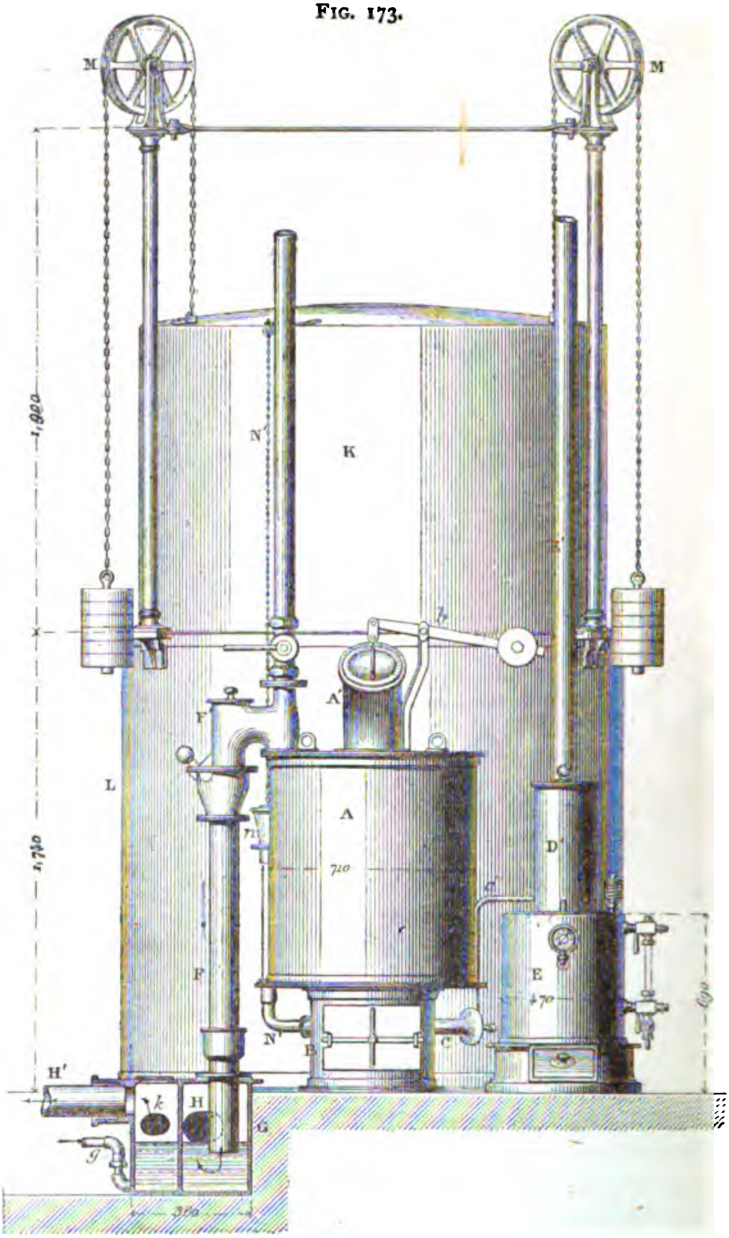
FIG. 172.



DOWSON GAS PLANT (PLAN).

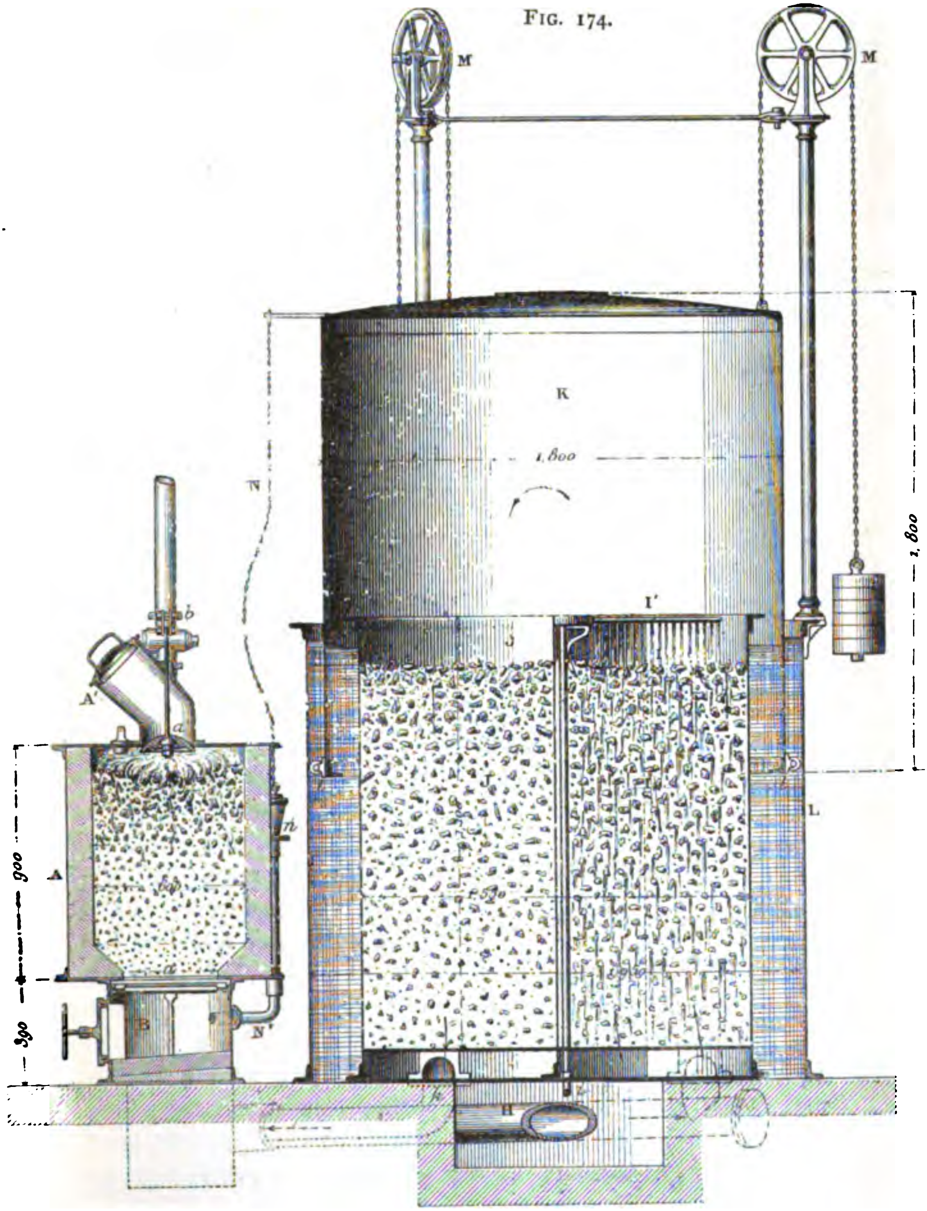
Hence a definite mixture of air and steam is carried into the closed space B underneath the fire-bars of the furnace. The pressure of the steam varies from 25 to 50 lb. per square inch above the atmospheric pressure, according to the size of the apparatus used, and the rate at which gas is required to be made. This pressure forces the mixture of steam and air

FIG. 173.



DOWSON GAS PLANT (ELEVATION).

FIG. 174.



DOWSON GAS PRODUCER WITH GASHOLDER AND SCRUBBER.

upwards through the incandescent fuel in the generator A. The steam ($H_2O$) is decomposed in presence of the incandescent carbon, becoming hydrogen and oxygen. The hydrogen is then free and passes off. The oxygen from the steam, as well as that from the air, combines in the first instance with the carbon of the fuel to form carbonic acid ($CO_2$). As this $CO_2$ rises through the hot fuel it is reduced to carbonic oxide (CO), two volumes of the latter being formed from one of carbonic acid, thus—

$$CO_2 + C = 2CO.$$

The liberated oxygen combines again, partly with some of the carbonic oxide to become carbonic acid, and partly with carbon to form carbonic oxide.

The gas coming off from the furnace is a mixture of carbonic oxide and hydrogen largely diluted with nitrogen from the air, and to a slight extent with carbonic acid which has escaped reduction; there are also very small percentages of hydrocarbons, such as marsh gas and olefiant gas, the quantity depending on the nature of the fuel used.

The gas used in the internal combustion engine should be *clean and free from sulphur compounds*, and it must be cooled to give a large amount of energy per unit volume in the cylinder. Hence, for such purposes it is best to use *anthracite* coal, which, being nearly pure, does not contain sulphur nor yield much ammonia, tar, or other products which readily condense and foul the pipes and valves. Good anthracite is also suitable fuel in the generator, because it makes a dense fire, free from holes or passages, and it does not cake nor yield much clinker. Ordinary *gas coke*, free from sulphur, which does not yield large quantities of clinker and which has been subjected to high temperatures in the retorts, has also been used to make Dowson gas. This gas cannot burn with a smoky flame, and there is no soot deposited—an advantage which renders it specially valuable for heating purposes, and is of the utmost importance for the cylinder and valves of an engine.

The *gas is cleansed* by passing it through water in the hydraulic box G and the **coke scrubbers** I and J, the former of which is kept wet by water from the spray-pipes I′. To render the plant compact, so as to occupy as little ground space as possible, these scrubbers are placed inside the gasholder tank, as shown in section in Fig. 174.

The valve *n* regulates the supply of steam to the generator and, within certain limits, governs automatically the production of gas by the rise and fall of the gasholder, and this not only avoids waste of fuel, but renders the storage of much gas unnecessary. When the valve *n* is lifted, by the chain N attached to the holder, some of the mixture of steam and air in B is blown off, so that less of it passes through the fire and consequently less gas is made. The valve is lifted when the holder is full, and is lowered again as the latter gets emptied.

The production of the gas is very rapid; thus at the works of Messrs. Crossley, a single generator, 9 feet high by 6 feet diameter, is able to make about 20,000 cubic feet of Dowson gas an hour. The complete plant, Figs. 172 and 173, large enough for a gas engine developing 50 indicated horsepower, occupies a ground space of only 9 ft. × 10 ft., in other words, not more than that required for a horizontal boiler of equal power.

The quality of the gas made by different producers can only be strictly compared when the same fuel is used under like conditions in each. However, the analyses given in the table, page 384, show the quality of the gas made from the different fuels, and enable us to form an opinion as to the applicability of each to the gas engine.

The table on page 385 gives an analysis by Professor William Foster of gas made in the Dowson apparatus with the cheapest or "pea"-sized anthracite; also an analysis of ordinary 16 candle-power coal gas; and the calculated calorific powers of both gases, so that a comparison may easily be made.

ANALYSES OF PRODUCER GASES.

| No. | Producer. | Fuel Used. | Percentage Composition by Volume. | | | | | Percentage of Combustible. | Authority. |
|---|---|---|---|---|---|---|---|---|---|
| | | | CO. | H. | $CH_4$, &c. | $CO_2$. | N. | | |
| 1 | Ebelmen .. | Wood with air .. .. .. | 32·4 | 10·3 | .. | 7·2 | 50·1 | 42·7 | Ebelmen and Grüner. |
| 2 | ,, .. | Peat or turf with air .. .. | 21·8 | 7·7 | .. | 9·0 | 61·5 | 29·5 | ,, |
| 3 | ,, .. | Lignite ,, .. .. | 32·8 | 4·3 | 3·0 | 2·1 | 57·5 | 40·1 | ,, |
| 4 | ,, .. | Coal ,, .. .. | 23·5 | 8·0 | 25·0 | 4·1 | 61·9 | 56·5 | ,, |
| 5 | ,, .. | Anthracite ,, .. .. | 22·0 | 2·5 | 2·0 | 4·0 | 68·5 | 26·5 | ,, |
| 6 | ,, .. | Coke ,, .. .. | 33·5 | 1·5 | .. | 0·9 | 64·1 | 35·0 | , |
| 7 | Siemens .. | Coal ,, .. .. | 24·2 | 8·2 | 2·2 | 4·2 | 61·2 | 34·6 | Krauss. |
| 8 | ,, .. | Coke ,, .. .. | 26·0 | .. | .. | 4·5 | 68·0 | 26·0 | Felix Leblanc. |
| 9 | ,, (new type) | Coal with steam-jet and air .. | 24·4 | 8·6 | 2·4 | 5·2 | 59·4 | 35·4 | G. J. Snelus. |
| 10 | Wilson .. .. | Durham coal with steam and air | 26·89 | 11·55 | 1·45 | 4·0 | 56·11 | 39·89 | Pattinson and Stead. |
| 11 | ,, .. .. | Fine Yorkshire slack ,, ,, | 23·41 | 13·82 | 2·22 | 4·69 | 55·86 | 39·45 | ,, ,, |
| 12 | ,, .. .. | Belgian coal ,, ,, | 23·60 | 10·55 | 3·05 | 5·25 | 57·55 | 37·20 | Manager of Hainault Glass Works. |
| 13 | Dowson .. | Trimsaran anthracite ,, ,, | 22·2 | 19·3 | .. | 5·8 | 52·7 | 42·0 | H. L. Greville. |
| 14 | ,, .. | Garnant ,, ,, ,, | 25·07 | 18·73 | 0·62 | 6·57 | 49·0 | 44·42 | W. Foster. |

TABLE OF COMPARISON.

| COMPOSITION. | Coal Gas. | | | Dowson Gas. | | |
|---|---|---|---|---|---|---|
| | Volume per cent. at 0° C. and 760 m.m. | Weight in Grammes of 100 litres. | Calorific Power of 100 litres. | Volume per cent. at 0° C. and 760 m.m. | Weight in Grammes of 100 litres. | Calorific Power of 100 litres. |
| Hydrogen .. H | 51·81 | 4·63 | 159,559 | 18·73 | 1·67 | 57,689 |
| Marsh gas .. $CH_4$ | 35·25 | 25·20 | 329,187 | 0·31 | 0·22 | 2,899 |
| Olefiant gas $C_2H_4$ | 3·53 | 4·41 | 52,664 | 0·31 | 0·38 | 4,633 |
| Carbonic oxide CO | 8·95 | 11·20 | 27,854 | 25·07 | 31·36 | 77,992 |
| Carbonic acid $CO_2$ | .. | .. | .. | 6·57 | 12·91 | .. |
| Oxygen .. $O_2$ | 0·08 | 0·11 | .. | 0·03 | 0·04 | .. |
| Nitrogen .. N | 0·38 | 0·47 | .. | 48·98 | 61·27 | .. |
| | 100·00 | 46·02 | 569,264 | 100·00 | 107·85 | 143,213 |

Here the percentage of carbonic acid is rather higher, and that of the carbonic oxide consequently lower, than when larger coal is used. With the latter the volume of $CO_2$ is usually from 4 to 5 per cent.

**Carbonic oxide,** CO, **is a very poisonous gas, devoid of odour.** It has a great heating power, being nearly as good as hydrogen. We see it is present in coal gas, but in much larger proportions in Dowson gas and water-gas, rendering these both strongly poisonous, and the incautious use of them dangerous. An atmosphere containing 1·5 per cent. of Dowson gas is fatally poisonous, and 3 parts per thousand produce symptoms of poisoning. Dowson gas has a characteristic though very slight smell, not readily detected, unless traces of sulphur be present in the fuel to form sulphuretted hydrogen. Such deadly gas must be well odorised; but with the proper precautions of sound gas fittings and ventilation, it is being used extensively, with few fatal results, in America, on the Continent, and in this country, proving both useful and economical as a fuel, at a cost of about *2d.* per 1000 cubic feet.

Coal gas can be easily detected by its odour. From the above table it will be seen that the coal gas has nearly four times the heating power of the Dowson gas, the comparative explosive force of the two gases in atmospheric air being as 3·8 : 1, that is, coal gas gives out on burning about four times more energy than the same volume of Dowson gas.

For the purpose of determining the probable nature of the chemical actions going on in the generator, we take the following data from a paper read by Mr. Dowson before the Institution of Civil Engineers. In one hour, 13 lb. anthracite, 7 pints of water, together with air, produce 1000 cubic feet of Dowson gas, or let us say—

| | | |
|---|---|---|
| 251 | cubic feet of | carbonic oxide |
| 187 | „ | hydrogen |
| 66 | „ | carbonic acid |
| 490 | „ | nitrogen |
| 3 | „ | marsh gas |
| 3 | „ | olefiant gas. |

With 490 cubic feet of nitrogen, 130 cubic feet of oxygen must have entered the furnace, or 620 cubic feet of air. Considering the reactions that take place to be—

$$2H_2O = 2H_2 + O_2 \quad \ldots\ldots \quad (1)$$

$$CO_2 = C + O_2 \quad \ldots\ldots \quad (2)$$

$$2CO_2 = 2CO + O_2 \quad \ldots\ldots \quad (3)$$

$$2CO = 2C + O_2 \quad \ldots\ldots \quad (4)$$

In 1000 cubic feet of the gas we have

66 cub. ft. carbonic acid, which required 66 cub. ft. of O by (2),
251 „ „ oxide „ 125·5 „ „ (4),

so that a total of 66 + 125·5 or 191·5 cubic feet of oxygen have been used to combine with carbon.

But the 187 cubic feet of hydrogen in the mixture were, by equation (1), combined with 93·5 cubic feet of oxygen in the steam before passing through the incandescent fuel. Hence, altogether 130 + 93·5 or 223·5 cubic feet oxygen went into the furnace, and 191·5 are accounted for. A quantity of steam, passing through the incandescent fuel, becomes 187 cubic feet of hydrogen and 93·5 cubic feet of oxygen (reduced to the ordinary pressure and temperature); the oxygen combines somewhere, it is difficult to say where, possibly through the formation of $CO_2$ as a vehicle, with carbon sufficient to form 187 cubic feet of carbonic oxide. Now the 620 cubic feet of air passing through the incandescent fuel contain 130 cubic feet of oxygen. Of this, 98 cubic feet combine with carbon sufficient (by reaction 2) to form 98 cubic feet of carbonic acid, which, as it rises, or without rising into the region of higher temperature, becomes dissociated (by reaction 4) into 98 cubic feet of carbonic oxide and 49 cubic feet of oxygen. Then 33 cubic feet of this oxygen combine again (reaction 3) with 66 cubic feet of the carbonic oxide to form 66 cubic feet of carbonic acid, and the other 16 feet of oxygen combine with carbon somehow (reaction 4) to form 32 cubic feet of carbonic oxide.

Thus altogether we have

187 cubic feet of hydrogen,
187 + 32 + 32, or 251 cubic feet of carbonic oxide,
66 cubic feet of carbonic acid,
490 „ nitrogen.

This required

620 cubic feet of air
and 187 „ steam.

As regards the weights of the substances, we have in CO 12 parts by weight of C + 16 of O, forming 28 of CO, therefore the carbon in CO weighs $\frac{12}{28}$ or $\frac{3}{7}$ of the whole. Similarly, the carbon in $CO_2$ weighs $\frac{12}{44}$ or $\frac{3}{11}$ of the whole.

Now 1 cubic foot of CO weighs about ·0784 lb., and 1 cubic foot of $CO_2$ weighs ·0784 × $\frac{11}{7}$ or ·1232 lb., so that 251 cubic feet of CO weigh 251 × ·0784 or 19·68 lb., and 66 cubic feet of $CO_2$ weigh 66 × ·1232 or 8·13 lb. Therefore of carbon we have $\frac{3}{7}$ of 19·68 or 8·43 lb. in the CO, and $\frac{3}{11}$ of 8·13 or 2·22 lb. in the $CO_2$. Hence the total 8·43 + 2·22 or 10·65 lb. of carbon actually goes off as CO and $CO_2$; and thus of the 13 lb. anthracite put into furnace we get this amount (10·65 lb.) accounted for, neglecting the carbon that goes off as marsh gas and olefiant gas. This average coal consumption of 13 lb. per 1000 cubic feet includes all sources of waste, etc.

Again, to calculate the water consumption: we require (by reaction 1) 187 cubic feet of steam ($H_2O$) to give off 187 cubic feet of $H_2$. In $H_2O$ there two parts by weight of hydrogen + 16 of O, forming 18 of $H_2O$, and the hydrogen is only $\frac{2}{18}$ or $\frac{1}{9}$ of the whole weight of steam. But 1 cubic foot of hydrogen weighs ·0056 lb.; therefore the weight of water utilised to give off 187 cubic feet of hydrogen is 187 × ·0056 × 9, or 9·42 lb.

Now 8 pints or 1 gallon of water weighs 10 lb., and Dowson states that he puts in 7 pints per 1000 cubic feet, that is, $\frac{7}{8}$ of 10 lb. or 8·75 lb. Probably the difference 0·67 lb. of water comes from the fuel. Hence we see, on the whole, the analysis of Dowson gas bears out the theoretical chemical reactions and dissociation assumed to take place.

Let us now consider the complete combustion of 1 cubic foot of Dowson gas, taking analysis page 385, and make a similar comparison to that given for coal gas, page 369. Here we see that, for complete combustion,—

Equation (1) 0·1873 c. ft. hydrogen needs 0·0936 c. ft. O, giving 0·1873 c. ft. water vapour.
,, (2) 0·0031 c. ft. marsh gas needs 0·0062 ft. O, giving 0·0062 ft. $H_2O$ + ·0031 ft. $CO_2$.
,, (3) 0·2507 c. ft. carbonic oxide needs 0·1254 ft. O, giving 0·2507 c. ft. $CO_2$.
,, (4) 0·0020 c. ft. olefiant gas needs 0·0060 ft. O, giving 0·0040 c. ft. $CO_2$ + ·0040 ft. $H_2O$.
,, (5) 0·0011 c. ft. tetrylene gas needs 0·0066 ft. O, giving 0·0044 c. ft. $CO_2$ + ·0044 $H_2O$.
The carbonic acid and nitrogen do not burn.

The results tabulated give :—

COMBUSTION OF DOWSON GAS.

| CONSTITUENTS. | | Volume of Constituent in 1 cubic foot of Dowson gas. | Heat evolved (lb. degree C.) | | Oxygen required. | | Volume of Products of Combustion. | |
|---|---|---|---|---|---|---|---|---|
| | | | Cubic foot of each gas. | By amount of each present. | By 1 cubic foot of each gas. | By given amount of each. | Per cubic foot of each. | Per given amount of each. |
| Hydrogen .. .. | H | 0·1873 | 191·13 | 35·79 | 0·5 | 0·0936 | 1 | 0·1873 |
| Marsh gas .. | $CH_4$ | 0·0031 | 584·36 | 1·81 | 2 | 0·0062 | 3 | 0·0093 |
| Olefiant gas .. | $C_2H_4$ | 0·0020 | 932·05 | 1·864 | 3 | 0·0060 | 4 | 0·0080 |
| Tetrylenes .. | $C_4H_8$ | 0·0011 | 1702·00 | 1·872 | 6 | 0·0066 | 8 | 0·0088 |
| Carbonic oxide .. | CO | 0·2507 | 190·02 | 47·638 | 0·5 | 0·1254 | 1 | 0·2507 |
| Non-combustibles | $\left\{ \begin{matrix} \text{N and} \\ CO_2 \end{matrix} \right.$ | 0·5555 | .. | .. | .. | .. | .. | 0·5555 |
| | | | | 88·974 | | 0·2378 | | 1·0196 |

Hence, to burn one cubic foot of Dowson gas, we must have 0·2378 cubic foot of oxygen or 1·1324 cubic feet of air, so that the mixture of 2·1324 cubic feet of air and gas before combustion becomes changed into—

0·2019 cubic foot water vapour,
0·2622 „ carbonic acid,
0·0657 „ „ in gas,
0·4898 „ nitrogen in gas,
0·8946 „ „ in air,

or 1·9142 cubic feet after combustion.

Taking into account the products of past combustions filling the clearance space, we have, say, 4 cubic feet becoming 3·7818 cubic feet, or contracting by nearly 5½ per cent. of its volume.

This change is greater than in the case of coal gas, and we have less right, when using Dowson gas, to assume, as we do for all practical purposes, that there is no diminution, and that the fluid in the gas engine, from the beginning of its compression until it is allowed to escape, behaves like a perfect gas receiving heat from an outside source.

Dowson gas is well adapted to drive gas engines, and is largely used for this purpose with very economical results. In 1885, the Delamare-Deboutteville gas engine, known as the "Simplex" motor, tested at Rouen by Professor Witz, during a two hours' run under ordinary practical conditions of working, gave 7·22 useful horse-power on the brake, with an average consumption per brake horse-power of 2459 litres, or 86·84 cubic feet of Dowson gas at 0° C. and 760 m.m., equal to 1·3 lb. of coal per brake horse-power per hour. Of 3116 units of heat available, 635, or 20 *per cent., were transformed into useful effective work.* This surpasses the performance of the best steam engine and boiler. Still more favourable results have been obtained. Another "Simplex motor" driven by Dowson gas at Marseilles gave 59 useful horse-power on the brake, with an average consumption of 2200 litres, or 77·7 cubic feet of this gas per brake horse-power per hour. Under the usual working conditions, this "Simplex motor" driven by Dowson gas, gives 40 horse-power with a consumption of 23 kilogrammes of ordinary anthracite per hour, that is, 1·265 lb. per horse-power per hour.

At the Crossley Brothers' works, Openshaw, the Otto engine is driven very satisfactorily by *Dowson gas made from ordinary gas coke*, at a consumption of *under 2 lb.* per indicated horse-power per hour. The price of the coke is *7s. 6d.* per ton delivered, so that the cost is less than 0·08*d.* per indicated horse-power per hour. A comparison of Dowson gas with Openshaw town gas was made in driving a nominal 9 H.P. Crossley engine, cylinder 9½ inches diameter, stroke 18 inches, and speed 160 revolutions per minute.

| | Average Indicated H.P. | Explosions per cubic foot of gas. | Gas used, cubic feet per H.P. | Temperature of gas. |
|---|---|---|---|---|
| Coal gas .. .. .. | 18·16 | 13·6 | 19·4 | 56° F. |
| Dowson gas.. .. | 18 | 3·2 | 83·4 | 66° F. |

Therefore the actual consumption of coal gas is one-fourth that of Dowson gas when corrected for temperature.

Since the Dowson gas requires much less air for its combustion than coal gas, it is possible to pass into the ordinary cylinder of the internal combustion engine the additional quantity required, by increasing the size of the gas supply passage, diminishing the air supply, allowing an ample excess of air to insure complete combustion and to develop the same power as with coal gas, notwithstanding the higher heating power of the latter. Hence, although at first sight it may, perhaps, be thought that, as so much more of the Dowson gas is required than of coal gas, the cylinder of the engine must be enlarged, this is not so, and it is found that the same cylinder will do for either gas. Besides, in order to ensure combustion and efficient working with an internal combustion engine using this gas it is necessary to increase the compression up to 3·5 atmospheres at least before ignition.

Calculations of the specific heats, similar to those given above for coal gas, made for the usual mixture of Dowson gas with air and the products of previous combustions, as in the Otto engine cylinder, show that the ratio of the specific heats $\gamma = 1 \cdot 385$, and $\gamma = 1 \cdot 364$ for the products after combustion.

## OIL-GAS.

In 1815, Mr. John Taylor, of Stratford, Essex, patented an apparatus for the manufacture of gas from vegetable and mineral oils. It consisted of a funnel to contain the oil, and two cast iron pipes or retorts heated in a fire place. The oil vaporised in the first pipe was further distilled on ascending through the second pipe to the gas holder.

Gas is now generally made from *intermediate oil*, by passing it in a thin continuous stream through a pipe, where it is *vaporised* in a *retort* at a *cherry red* heat, which *decomposes* and converts it into a "fixed" or permanent *gas*. This gas is then passed through a *hydraulic main* filled with water, which *separates* the *tarry products*, and after further *washing* it is finally dried and *purified* by passing it over a mixture of slaked lime and sawdust, on its way to the gasholder, where it is *cooled* and stored ready for use. The quality of the gas and the number of cubic feet obtained per gallon of oil depend upon the temperature of the retort and upon the rate at which the oil is allowed to run into it. In fact, every oil requires special treatment, in order to yield the best gas. Once-refined paraffin oil yields, at a bright cherry red, about 90 cubic feet of 60-candle gas; with a yield of 120 cubic feet the gas was only 40-candle, whilst at a bright orange red, 150 cubic feet of about 25-candle gas was produced.

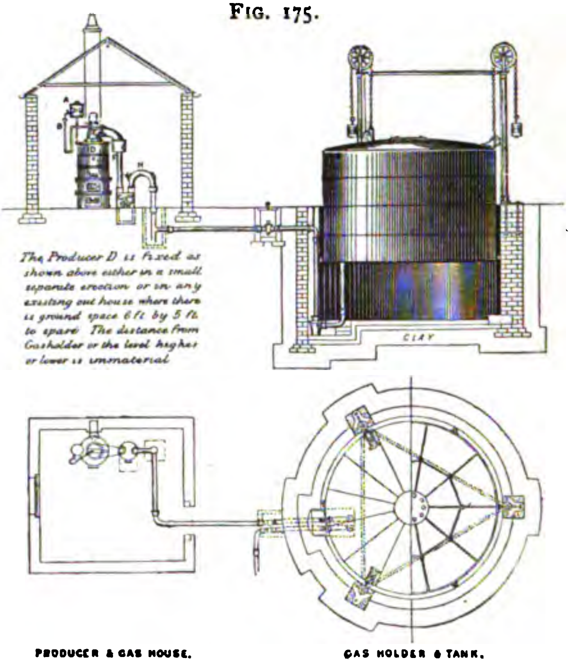
### Mansfield Oil-gas.

The MANSFIELD OIL-GAS APPARATUS is very simple, cheap, and compact. It makes gas from fats as well as from mineral and vegetable oils.

The arrangement of the complete plant is shown in Fig. 175, and an outside view of the **Producer** in Fig. 176, with a sectional elevation in Fig. 177.

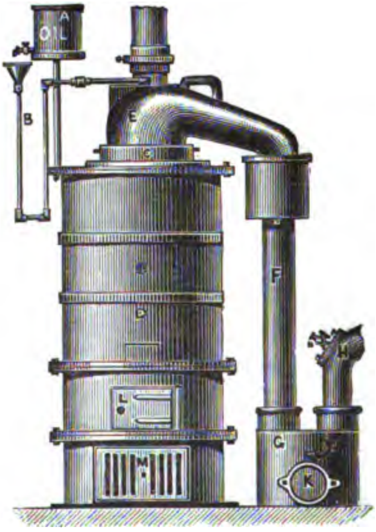
The *Producer* or gas generator has a strong cast-iron casing D, lined inside with moulded fire clay blocks P (Fig. 177). The cast-iron retort C, hangs by a flange on the fire clay cover, and can be lifted out or replaced in a few minutes.

FIG. 175.



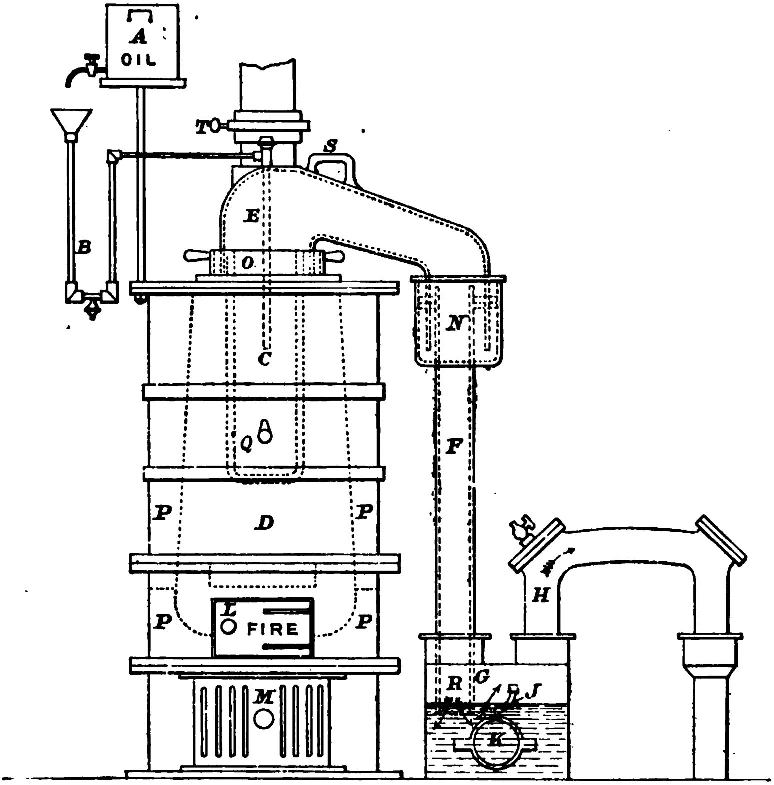
*The Producer D is fixed as shown above either in a small separate erection or in any existing out house where there is ground space 6 ft by 5 ft to spare. The distance from Gasholder or the level higher or lower is immaterial*

FIG. 176.



The retort is heated and kept up to the desired temperature, from 1600° to 1800° F., a bright cherry red, by a fire of coal, coke, wood, or other fuel, placed on bars at L and regulated to a nicety by the sliding grids M and the damper T, the colour of the retort being observed through the sight hole Q. These retorts usually last two years with moderate use; the iron casings are made solid and durable, and the fire clay blocks last for years. The trouble of screwing up and making joints in the ordinary way is obviated by the simple

FIG. 177.



MANSFIELD OIL-GAS APPARATUS.

expedient of a socket in top of the retort at O, filled with melted lead, and a socket on top of the stand-pipe at N, kept filled with water. These are arranged to prevent the escape of gas, acting at the same time as safety valves, because whenever any extraordinary back pressure occurs, the gas forces its way out at N or J. The lower end R of the stand-pipe dips into water in the hydraulic box G, which is regulated by the ½-inch siphon bend J. Any accumulation of tar can be cleared out occasionally at the door K.

All the parts are made to fit exactly, so that they can be easily fixed together, and the whole apparatus is so simple that it can be managed by an unskilled labourer of ordinary intelligence.

**To make Gas,** the usual procedure is to light the fire below the retort the first thing in the morning and keep up a regular heat until the lead in the ring space O on the top of the retort is all melted, a sign that a sufficiently high temperature has been attained for the manufacture of the gas. The large end of the bonnet E sinks into the melted lead, automatically making a gas-tight joint, the small end of the bonnet E being in the water joint at N.

The can or cistern A is filled with *oil* or *melted fat*, which trickles into the funnel and through the ½-inch siphon pipe B, in a thin continuous stream, $\frac{1}{16}$ of an inch thick, into the upper part of the retort. The oil is *vaporised* in this pipe, and the oil-vapour, passing down the interior into contact with the sides of the retort at a cherry-red heat, is *decomposed or converted into "fixed" gas.* The gas, after leaving the retort, passes through the bonnet E, down the stand-pipe F into the water in the hydraulic box G, where tarry or other condensable products are separated, and thence by the arch-pipe H and connecting pipes to the gas-holder, where it is stored and when *cool* is ready to be used for heating or motive power without any further treatment being necessary.

A gentle pulsation of the lead at O and in the water at N and J, is an indication of successful gas making, and the quality of the gas can be roughly tested at the small tap in the arch-pipe H.

In the manufacture of oil-gas the retort must be *kept uniformly* at the *proper temperature*, because the quality of the gas produced depends more upon this than upon the quality of the oil used. The temperature is regulated by the sliding grids M and the damper T, and the gas made from coal oil is pure and does not readily condense.

*To stop gas-making* turn off the oil tap and remove the oil cistern from its stand. Let the fire cool down gradually, keeping the furnace door closed, about 15 minutes. Shut the main cock leading to the gas-holder. Then, before the lead sets, lift out the bonnet E by the handle S, any residual gas being allowed to burn, and when cool, the retort, bonnet, and stand-pipe can be examined and cleared out if necessary with a scraper.

In the United Kingdom the oils mostly used are the Scotch *intermediate oils*, so called because in flashing point and density they lie between burning oils and lubricating oils. This refuse of heavy paraffin from the Scotch distillers is of specific gravity 0·840 to 0·865 and lowest flashing point (close test) 235° F. or 105° C. The oil is *inexplosive* and free from offensive smell. The Mansfield apparatus makes **1000 cubic feet of gas from 7 to 9½ gallons of intermediate oil,** which costs £5 per ton, or about 4½*d.* per gallon, at the oil works. The cost of fuel in the furnace comes to less than 1*d.* per 100 cubic feet of gas made, so that the total cost of fuel and mineral oil to make the gas is about 6*d.* per 100 cubic feet. Now, Messrs. Crossley Brothers state that with their 12 H.P. (nominal) Otto engine, the consumption of the Mansfield gas is 9 cubic feet per indicated H.P. per hour, or say, 10 cubic feet per brake H.P. per hour. Hence the total cost of fuel used by the combination of Otto gas engine and Mansfield apparatus with intermediate oil is about 0·6*d.* per brake H.P. per hour.

This combination is being used at Jerusalem, and the gas is made from various kinds of fatty refuse. In Australia and

South America, where mutton fat is of little or no value, gas is being made from it, with wood as fuel. At the Melbourne Exhibition in 1888 dirty dripping of fat that would not flash at a temperature of 400° F. (nearly 204·5° C.) was melted and kept fluid by a burner under the oil can. This made an abundant supply of excellent gas, driving an Otto engine and suitable for various purposes, as heating and lighting.

In India, Rangoon or Castor oils may be used. A natural oil is found in the West Indies, 1 gallon of which yields 80 cubic feet of gas, equal in purity and power to that from coal oil; whilst on the West Coast of Africa 10 lb. of palm oil yield 100 cubic feet of gas.

It thus appears that the Mansfield oil-gas apparatus, by converting oil into gas, effects a considerable saving in fuel, besides avoiding disagreeable smells.

This plan of gas-making has been adopted at Shanghai Arsenal and by the Japanese Government, and is in use at many private houses and works.

## Keith's Process.

The practical solution of the problem of driving gas engines successfully on a large scale by rich mineral-oil gas, took place at Langness Point, Isle of Man, where the first oil-gas installation was used to work fog-signals for the Commissioners of Northern Lights. The success of this undertaking led to the still larger and more important oil-gas installation at Ailsa Craig Lighthouse on the Firth of Clyde.

In both of these the oil-gas apparatus was supplied by Mr. JAMES KEITH, of Arbroath, Scotland, to whom several patents have been granted in connection with the manufacture and application of mineral oil-gas. On Ailsa Craig Rock, the gas works, while on test, made 3500 cubic feet of rich (60-candle) oil-gas per hour, being at the rate of 300 cubic feet per hour per retort. Three gas-producers were used, each having four retorts and one fire. Usually the rich gas is made at the rate of 186 cubic feet per retort per hour, with ordinary paraffin oil yielding 100 cubic feet per gallon, whilst a thick blue oil gave 150 cubic feet of gas to the gallon with the same temperature of retort.

In KEITH'S PROCESS the gas is **made rapidly, washed thoroughly,** and then **quickly cooled;** the objects in view being: (1) the maximum yield of gas, with the minimum consumption of fuel for heating the retorts; (2) a cool and permanent gas capable of being used continuously as it is being made, without leaving any deposit, and (3) with the smallest possible attention in working.

In the manufacture of oil-gas the quality of the oil used is important, as well as uniformity in the temperature of the retorts. The best temperature is a bright cherry-red heat, and any irregularity in heating seriously affects the quality of the gas. When the retorts are not sufficiently heated, or the oil not properly converted into gas, a large quantity of tar is given off, and a drop of this on white paper has a greasy border; on the other hand overheating separates carbon as soot.

After the oil has been "fixed," or converted into permanent gas in the cast iron retorts, it is thoroughly washed, to remove all the tarry and condensable products, by passing it through the hydraulic main, condenser, washer, and cooler, on its way to the gasholder.

This rich, cool gas, on leaving the gasholder, is passed through Keith's *meter-mixer*, which automatically adds 35 parts of air to every 65 parts of gas. This mixture, having about the same heating power as ordinary coal-gas, drives gas engines with more regularity than when the rich oil gas is used directly. On Ailsa Craig, six Otto gas engines, each of 8 H.P. nominal, use this mixture of air and gas at the rate of 26 cubic feet per actual H.P. per hour.

The cost of the paraffin oil is 4½*d.* per gallon, yielding 100 cubic feet of rich gas; to this must be added the price of coal for heating the retorts, reckoned at 9·6*d.* per cwt. delivered, and 20 to 30 cwt. of coal required for 10,000 cubic feet of gas, brings up the cost of the rich oil gas to about 6·9*d.* per

100 cubic feet, exclusive of wages, interest on capital, and depreciation of plant. Thus the consumption of 26 cubic feet of the mixture containing 16·9 cubic feet of the rich oil gas, makes the cost 1·16*d.* per H.P. per hour on an isolated rock like Ailsa Craig, where freight and cost of landing are serious considerations. This oil gas is also employed for lighting.

### OIL AND WATER GAS.

We have already seen that steam is injected into the furnace with oil when this is used for heating purposes. Many arrangements have been devised for the production of a permanent gas from a mixture of oil and steam. In the method of manufacture of gas employed by Messrs. Rogers, of Watford, **oil is injected into red-hot retorts by means of steam jets.** The retorts are kept at a high temperature to produce a permanent gas. The steam is made by the waste heat from the retort furnace. In the retorts the steam is decomposed in presence of the carbon of the oil, which combines with the oxygen to form carbonic oxide, so that the deposit of solid carbon in the retort is to a great extent prevented. The other parts of the process are much the same as those described above.

In this way, "intermediate" oils may be completely made into permanent gas, leaving no tar or condensable liquid, with a yield of nearly 300 cubic feet per gallon Messrs. Rogers, using an intermediate oil, flashing at 250° Fah. (121° C.), produced with their apparatus from one gallon of oil, 120 cubic feet of gas, which gave the analysis on next page.

In round numbers the heating value of this oil-gas is 483 heat-units per cubic foot, that is, $483 \times 120 = 57{,}960$ heat-units from one gallon of intermediate oil, more than 5 times the heat value of the original oil. If we assume that the hydrocarbons in this oil gas consist of olefiant gas (ethylene $C_2H_4$) and tetrylene ($C_4H_8$) in the ratio of 2 to 1, then the calculated heating power becomes a much higher figure, 524 heat-units per cubic foot of oil-gas.

COMPOSITION AND HEAT VALUE OF ROGERS' OIL-GAS.

| CONSTITUENTS. | | Volume of Constituent in 1 cubic foot of Oil-gas. | Heat Value per cubic foot of Constituent. | Heat Value of given amount of each in Oil-gas (lb. degree C. heat units). |
|---|---|---|---|---|
| Hydrogen .. .. .. .. .. .. .. | $H$ | 0·3161 | 191·13 | 60·40 |
| Marsh gas .. .. .. .. .. .. .. | $CH_4$ | 0·4617 | 584·36 | 269·80 |
| Luminiferous hydrocarbons .. .. .. | $C_2H_4$ | 0·1629 | 932·05 | 151·80 |
| Carbonic oxide .. .. .. .. .. .. | $CO$ | 0·0014 | 190·02 | 0·27 |
| Nitrogen .. .. .. .. .. .. .. .. | $N$ | 0·0506 | | |
| Oxygen .. .. .. .. .. .. .. .. | $O$ | 0·0073 | | |
| Total .. .. .. .. .. | | 1·0000 | .. | 482·27 |

In any case it is quite clear that a gas of very great heating power may thus be obtained from steam along with intermediate oils of specific gravity 0·840 to 0·870, or shale spirit, otherwise of very little value being refuse from the oil distillers.

## Pintsch Oil-gas.

The system ot making compressed oil-gas, and its extensive application in this country to the lighting of railway carriages (1876), buoys and beacons (1878), are chiefly due to Mr. Julius Pintsch, Berlin.

The method used by Pintsch to make gas from oil is much the same as those of Keith and Pope. The works usually consist of (1) a retort-house containing furnaces and benches; (2) a purifying house with air condenser or cooler, washer, lime purifier, and meter; (3) a gasholder; and (4) an engine-room with boiler, and a duplicate set of double-acting compression pumps.

The oil is pumped from a tank or barrel into a cistern on the top of the retort bench. The retorts are ⌓-shaped cast-iron tubes set in pairs, one above the other in brickwork, and the flame from the furnace plays on the tubes. The oil from the cistern flows through a siphon pipe and falls on a sheet-iron tray, along which it runs to the retort, passes through the tube as vapour, and is conducted to the lower or hottest retort, where it is "fixed," or rendered a permanent gas. It now passes down into the hydraulic main or tar pit filled with water, which separates part of the tar, and the gas next passes through the condenser and washer to remove the tar.

Finally, the gas is dried and cleansed of the sulphur compounds, carbonic acid, and sulphuretted hydrogen present, by passing through the purifier over a mixture of slaked lime and sawdust spread on perforated trays. It then passes through a meter to the gasholder.

The **yield of good gas from paraffin oil** of specific gravity 0·840 to 0·848 and flashing points 220° to 268° Fahr. (close test) varies from 70 to 90 cubic feet, when the retorts are kept at a bright cherry-red heat.

The gas is taken from the gasholder by double-acting compression-pumps and forced into steel gasholders at a pressure of 150 lb. per square inch, or about 10 atmospheres. The pump-barrels are kept cool by water-jackets. The quantity of hydrocarbon deposited, by compression to 10 atmospheres is 1 gallon per 1000 cubic feet.

The cost of making the gas varies from 6*s.* to 7*s.* per 1000 cubic feet, as made with large plant by the Metropolitan and other railway companies.

## CARBURETTED AIR.

Volatile petroleum spirit, such as gasoline, when finely divided into spray, so as to expose a large surface to contact with the air, readily evaporates or gives off inflammable vapours which, when heated and completely gasified, can be used directly as gaseous fuel in the motor cylinder of the internal combustion engine.

Liquid petroleum of low density, from 0·650 to 0·700, can be rapidly vaporised in various ways. In conjunction with the Lenoir petroleum engine, as described above, the

**carburator** consists of a cylindrical vessel, having a drum inside it, provided with little troughs or buckets which lift the liquid petroleum, as the drum is rotated, and dash it back in fine spray, air being drawn through this cylinder to aid evaporation. The drum is driven by the engine. The trouble with this method of carburetting air is, that the most volatile constituents pass off first, leaving at last a heavy useless residuum. The vapours also carry off with them some organic and mineral substances, which go to form a crust in the cylinder. The evaporation also tends to cool the remaining liquid, which thus becomes more and more difficult to evaporate.

In order to overcome these faults, Messrs. Delamare-Deboutteville and Malandin, of Rouen, allow the petroleum to trickle down through a spiral horsehair brush (page 73), fixed in a chamber heated by the hot water from the cooling jacket of the motor cylinder. Some of the **hot water falls with the petroleum on the horsehair brush** and absorbs the vegetable and mineral substances present, whilst the whole of the light petroleum spirit is volatilised, and the gas is sucked through a safety-valve directly to the motor cylinder. This combination is only recommended for small powers of engine with light petroleum spirit, where the latter is cheap and plentiful, or in very small installations for out-of-the-way country districts.

A more complete method of preparing inflammable vapour or gas from ordinary refined petroleum oil, and even from heavy creosote oil, has been worked out in a practical form by Messrs. Priestman in their *oil engine* or *hydro-carburetted air engine.* (Chapter IV.) When petroleum oil or distillate of specific gravity about ·820 is used directly in the oil engine, the mixture of inflammable vapour and air should be *heated in a* **separate vaporiser** to prepare it for ready ignition and complete combustion in the motor cylinder. Before starting the engine this is done by a heating lamp, and during working the necessary heat is supplied by the exhaust gases passing round this part of the vapour-chamber, after being driven out of the engine cylinder by the motor piston.

In order to evaporate the liquid hydrocarbon, in the first instance, a regulated supply of it from the oil reservoir, as well as of air to mix with it, are pumped under moderate pressure along separate passages leading to a mixing nozzle, surrounded by an air-chamber. The two passages for the oil and air are sometimes furnished with chambers, packed with cotton wool or suitable filtering material, through which the fluids are strained on their way to the mixing nozzle. The supply of air being kept constant, the richness of the charge can be controlled, according to the load on the engine, by a special valve, applied to the passage conveying the liquid hydrocarbon, and operated by a centrifugal governor which rises or falls with the speed.

By means of this mixing nozzle the oil and air are intimately mixed, and injected, in the form of fine spray, into the main vaporiser, where the mixture mingles with additional streams of air through fine holes surrounding the nozzle. The inflammable vapour and air are then admitted, by a non-return valve, into another compartment of the vapour-chamber, surrounded by a jacket through which the exhaust gases escape. There are thus *two compartments in the vapour-chamber*, separated by a thick partition of asbestos mill-board, or other suitable non-conductor, to prevent transmission of heat from the one to the other. This arrangement prevents the choking and stoppage of the minute holes for the spray and extra air supply to the main vaporiser, by a troublesome gumming deposit produced by heating some oils. The oil, being supplied in the proper proportions to suit the power of the engine, is finely divided into spray by the nozzle, and thus thoroughly mixed with air in the spray chamber. The inflammable mixture is then heated and completely vaporised in the other compartment of the vapour-chamber, which supplies the working charge to the engine.

This device is found to work well in practice, and permits the use of the common petroleum oil of commerce as fuel in the ordinary gas engine, without the danger of explosions which attends the storage and use of light volatile petroleum spirit.

## PRACTICAL RESULTS.

It has been calculated (page 369) that the total heat evolved in the complete combustion of all the constituents in 1 cubic foot of good coal gas amounts to about 378 units of heat, that is, equivalent to 378 × 1390, or 525,420 ft. lb. of energy.

This total amount of energy includes not only the ***latent heat of steam*** formed by the combustion of the hydrogen in ***all*** the hydrocarbons, which is given out on condensing the gaseous water, but also the heat derived by further cooling the liquid water, and all the products of combustion down to the ordinary temperature 18° C.

In the same way, 1 cubic foot of Dowson gas made from garnant anthracite gives out, in complete combustion, heat equivalent to 89 × 1390, or 123,710 ft. lb. of energy.

We may, therefore, take in round numbers, as roughly approximate values of the total heat-energy given out in the complete combustion of

One cubic foot of good coal gas = 525,000 ft. lb.
" " Dowson gas = 124,000 "

Further, it is seen (page 365) that 1 lb. of coal yields, on an average, about 4·5 cubic feet of coal gas, and this on burning gives out 525,000 × 4·5, or 2,362,500 ft. lb. of energy. This is not even a quarter of the total energy given out by 1 lb. of the parent coal in burning. The coke resulting from the distillation of coal is valuable as a heating agent, and can even be used with steam and air to make Dowson gas.

Again, 1 lb. of anthracite produces about 70 cubic feet of Dowson gas, capable of giving out on burning 70 × 124,000 or 8,680,000 ft. lb. It may be taken that 1 lb. of anthracite, if carefully and completely burnt, gives heat-energy equivalent to 11,000,000 ft. lb.

By similar calculations we may estimate the relative heating power of the different kinds of gas used to drive the internal combustion engine.

The quality and value of coal gas as a heating agent varies from day to day, because of slight irregularities in the temperature of distillation and time it is carried on, as well as by reason of want of uniformity in the quality of coal used. For instance, in the motor trials by the Society of Arts in London, 1888, the heat value of 1 cubic foot, under standard temperature and pressure, was 633 units (lb. degree Fahr.), equivalent to 488,676 ft. lb., on the 21st September, while on the 27th September it was 624 units of heat, or 481,728 ft. lb. Here the latent heat of steam has been deducted from the heat of combustion of hydrogen. The heat values per pound of gas varied from 19,830 to 19,200 units, that is, equivalent to 15,318,675 ft. lb. and 14,832,000 ft. lb. respectively.

Therefore, in a special test, it is necessary not only to measure the quantity of gas consumed, but also to determine, by chemical analysis, the composition of the gas, and then calculate the total amount of heat this gas is capable of giving out when completely burned.

The heating power of different samples of coal gas have been estimated as follows:—

| Description. | Foot-pounds per cubic foot. | Foot-pounds per pound. |
|---|---|---|
| Manchester coal gas .. .. .. | 505,000 | 15,147,000 |
| London " .. .. .. | 489,000 | 17,370,000 |
| Berlin " .. .. .. | 466,000 | 18,500,000 |
| Heidelberg " .. .. .. | 484,000 | 14,510,000 |

## Deductions.

We can now ask the important question:—

How many cubic feet of coal gas per hour give in burning one indicated horse-power?

If V cubic feet of gas be required per indicated horse power per hour, then the equivalent of the energy given out by its complete combustion is known in foot-pounds per minute, and

$$\frac{525{,}000 \times V}{60} = 33{,}000,$$

whence

$$V = \frac{33{,}000 \times 60}{525{,}000} = 3 \cdot 77 \text{ cubic feet.}\text{—}\textit{Answer.}$$

Similarly, for Dowson gas, we require *at least* $v$ cubic feet completely burned to give 1 indicated horse-power per hour,

$$\frac{124{,}000 \times v}{60} = 33{,}000,$$

whence

$$v = 16 \text{ cubic feet.}$$

Therefore,

3·77 cub. ft. of coal gas per hour is equivalent to 1 H.P.,

and

16 „ „ Dowson gas ,, „ „

In the same way, *assuming* that all the heat generated by the complete burning of coals can be utilised, it becomes an easy matter to calculate the consumption of coal per indicated horse-power per hour for any kind of coal, given its composition.

In practice, however, there are various sources of heat waste, and we shall see in Chapter XVI. that it is impossible to convert all the heat of combustion of a fuel into work.

The **apparent or absolute efficiency** *of any heat engine is the ratio of the indicated work done in the cylinder to the total quantity of heat generated by the fuel per minute.* Besides, part of the energy will be spent in overcoming the friction of the mechanism, heating the bearings, and the **mechanical efficiency** is the ratio of the effective power actually given on the brake to the indicated power developed in the cylinder of the engine.

We shall use the term *real* or **practical efficiency** to represent the fraction of the total power supplied by the fuel that is utilised as effective power on the brake.

The data given above enable us to judge of the efficient working of a gas engine, from its hourly consumption of gas per brake horse-power and per indicated horse-power.

## EXAMPLES.

1. The early Lenoir engine consumed 95 cubic feet of coal gas per hour per indicated horse-power given out. What is the absolute efficiency of this heat engine? If it had been a perfect heat engine it would have used only 3·77 cubic feet of coal gas per indicated horse-power per hour. Therefore its absolute or apparent efficiency is $\frac{3 \cdot 77}{95}$, or ·0396. That is, the Lenoir engine utilised nearly 4 per cent. of the total energy supplied to it.

2. A nominal 6 H.P. Clerk gas engine gave 9 indicated H.P. and 7·1 H.P. on the brake, with a gas consumption 24·5 cubic feet per hour per indicated horse-power, and consumption 31·0 cubic feet per hour per brake horse-power; find (*a*) its *real* or *practical* efficiency, (*b*) apparent or absolute efficiency as a gas engine, and (*c*) its mechanical efficiency.

(*a*) The brake is the actual useful horse-power given out, and therefore the *real* or *practical efficiency* is $\frac{3 \cdot 77}{31} = \cdot 1216$, or 12·16 per cent.

(*b*) The indicated is only apparent horse-power developed in the cylinder of the heat engine, so that the *apparent efficiency* is $\frac{3 \cdot 77}{24 \cdot 5}$, or ·1538, that is, 15·38 per cent.

(*c*) The efficiency of the mechanism is the fraction of the total power developed in the cylinder, that is, available on the brake attached to the fly-wheel. Clearly the smaller the fraction of power wasted in overcoming friction, the higher the mechanical efficiency.

We have in this case, $\frac{\text{brake horse power}}{\text{indicated horse-power}} = \frac{7 \cdot 1}{9} = \cdot 79$, or mechanical efficiency 79 per cent.

3. The Otto engine requires 82·5 cubic feet of Dowson gas per indicated horse-power per hour. What is its apparent or absolute efficiency?

*Answer:* $\frac{16}{82\cdot5}$, or 19·4 per cent.

4. In his small size generator Mr. Dowson uses 15 lb. of coal getting up steam in boiler and heat generator, 108 lb. coal during the day of 9 hours' working, actually converted in the furnace, and 17 lb. of coke in superheater per day. We may take the consumption as 140 lb. of anthracite for 9 hours—that is, 15·56 lb. per hour, producing 1000 cubic feet of gas per hour, and that an Otto engine uses 82·5 cubic feet of this gas per hour per indicated horse-power.

How many pounds of anthracite is this per indicated horse-power per hour?

Here 15·56 lb. of coal per hour is converted into 1000 feet of Dowson gas, which gives in the Otto engine $\frac{1000}{82\cdot5}$, that is, 12·1 indicated horse-power. Therefore one indicated horse-power is given by the consumption of $\frac{15\cdot56}{12\cdot1}$, or 1·285 lb. of coal per hour. The simplest and most direct method of reckoning cost of working is to take the coal consumed per horse-power per hour.

5. Further, in the combination of Otto gas engine with Dowson gas generator, for ordinary working, the average consumption of fuel, including all sources of waste, is 1·3 lb. per indicated horse-power per hour, and 1·5 lb. per brake horse-power per hour. What is the efficiency of the combination?

Now, one horse-power is the rate of doing 33,000 ft. lb. of work per minute, that is, 33,000 × 60, or 1,980,000 ft. lb. per hour. Energy is supplied by the coal burning at the rate of 1·3 × 11,000,000, or 14,300,000 ft. lb. per hour. Hence the apparent or absolute efficiency is $\frac{1{,}980{,}000}{14{,}000{,}000} = \cdot1385$, that is, 13·85 per cent.

Again, for one useful or brake H.P. we require 1·5 lb. coal, that is, 1·5 × 11,000,000, or 16,500,000 ft. lb. per hour.

Hence the real or practical efficiency, i. e. the fraction ot the total heat energy obtainable by the most careful burning of the coal, that is transformed into useful mechanical energy, is $\frac{1,980,000}{16,500,000} = 0{\cdot}12$, or 12 per cent.

6. An Otto gas engine has piston 12 inches in diameter and the length of crank 8 inches. When the speed is 160 revolutions per minute, with an explosion every two revolutions, consumption of London coal gas 533 cubic feet per hour, the mean pressure in cylinder, as found from the indicator diagram, is 62·2 lb. per square inch, and the useful work done, as measured on the brake, is at the rate of 18·3 horse-power; find the indicated horse-power efficiency of the engine, and the gas consumption per horse-power per hour.

Energy is supplied by the gas at the rate of $\frac{489,000 \times 533}{60}$ or 4,343,950 foot-pounds per minute.

The sectional area of the piston is $\pi r^2 = 3{\cdot}1416 \times 6 \times 6 = 113{\cdot}1$ square inches, so that the mean total pressure on the piston is 62·2 × 113·1 lb. whilst acted on by the burning and expanding gas, through the distance 2 × 8 inches = $\frac{4}{3}$ feet. The number of explosions per minute is 80, since there is only one explosion every two revolutions. Thus work is done upon the piston by the burning gas at the rate of $62{\cdot}2 \times 113{\cdot}1 \times \frac{4}{3} \times 80 = 750,460$ ft. lb. per minute. The same result is obtained by substituting the values in our formula:—

$$\text{Indicated H.P.} = \frac{plan}{33000} = \frac{62{\cdot}2 \times 4 \times 113{\cdot}1 \times 80}{3 \times 33,000} = 22{\cdot}74 \text{ H.P.}$$

Hence the apparent efficiency is $\frac{750,460}{4,343,950} = {\cdot}1727$, or 17·27 per cent.

Again, useful effective work is being done at the rate of 18·3 × 33,000 ft. lb. per minute as measured by the brake, and the *practical* efficiency is

$$\frac{\text{useful work done}}{\text{total energy supplied}} = \frac{18{\cdot}3 \times 3,3000}{4,343,950} = 0{\cdot}139, \text{ or } 14 \text{ per cent.}$$

The efficiency of the mechanism is

$$\frac{\text{useful brake H.P.}}{\text{indicated H.P}} = \frac{18\cdot 3}{22\cdot 74} = 0\cdot 8,$$

that is, 80 per cent.

We also see that the *gas consumption* per hour is at the rate of $\frac{533}{18\cdot 3}$, or 29·3 cubic feet per brake horse-power, and 29·3 × 0·8, that is, 23·44 cubic feet per indicated horse-power.

Assume that on an average 1 lb. of coal yields 4·5 cubic feet of this coal gas, and we find the *coal consumption* per hour to be at the rate of $\frac{29\cdot 3}{4\cdot 5} = 6\cdot 5$ lb. per brake horse power, or 5 lb. per indicated horse-power. We must bear in mind, however, that this does not represent *all* the energy obtained from the coal, since the coke, and especially the by-products in the manufacture of coal-gas, are very valuable and useful for many purposes.

7. A 16 horse-power nominal Otto engine, having piston 13 inches in diameter, length of crank 10·5 inches, used 784·6 cubic feet of coal-gas per hour when running at a speed of 151·37 revolutions per minute, with one explosion every two revolutions. The mean pressure in the cylinder during combustion, as found by indicator diagram, was 63·08 lb. per square inch, and the horse-power, measured on the brake, 27·75. Find (*a*) the indicated horse-power, (*b*) the apparent, and (*c*) the practical efficiency of the engine, also (*d*) the efficiency of the mechanism.

*Answer.*—(*a*) 33·6 H.P., (*b*) 16 per cent., (*c*) 13½ per cent., (*d*) 82·6 per cent. Here the *gas consumption per hour* is at the rate of 23·35 cubic feet per indicated horse-power, or 28·27 cubic feet per brake horse-power.

8. With the small two horse-power Otto engine, the quantity of coal-gas used per hour was 95·8 cubic feet. The diameter of piston 5·75 inches, and length of crank 6 inches. When the speed was 160·3 revolutions per minute and the mean pressure in the cylinder, as given by indicator diagram,

54·31 lb. per square inch, the effective horse-power on the brake was 2·87. Find (*a*) the indicated horse-power, (*b*) practical efficiency, (*c*) efficiency of mechanism, and (*d*) the gas consumption per hour per brake horse-power.

*Answer.*—(*a*) indicated horse-power 3·42, (*b*) 11·3 per cent., (*c*) 84 per cent. of indicated horse-power appears on the brake dynamometer, (*d*) 33·4 cubic feet of coal-gas per brake horse-power per hour.

9. In a trial of a 40 horse-power (nominal) twin-cylinder Otto engine driven by Dowson gas, Professor Teichmann, of the Royal Technical School, Stuttgart, and Mr. F. Böcking, Chief Engineer of the Rhenish Society for examining steam boilers, found the following:—

Diameter of cylinder 340 centimetres, travel of piston 600 m.m., length of brake-lever used 1·433 metre.

After running from 11 till 1 o'clock at an average speed of 140·4 revolutions per minute, with a weight of 191 kilogrammes on brake-lever, this load was then reduced to 181 kilogrammes and the average speed of the engine remained 140·5 revolutions per minute during four hours, from 1 till 5.12 o'clock.

The consumption of materials during the trials was:—

| | 11 till 1 o'clock. | 1 till 5.12 o'clock. |
|---|---|---|
| | kilogrammes. | kilogrammes. |
| Anthracite in generator .. .. .. .. | 74 | 136·5 |
| Coke in boiler and superheater .. .. | 8 | 19 |
| Water " " .. .. | 50 | 118 |

Calculate the fuel consumption per brake horse-power per hour.

*Answer.*—The effective power as measured on the brake is $\frac{2\pi \times 1·433 n W}{60 \times 75}$ chevaux vapeur, where $n$ is number of revolutions per minute and W the weight in kilogrammes on the brake.

Hence during the two hours, from 11 till 1 o'clock, the average effective power on brake was 53·63 horse-power, and the four hours, from 1 till 5 o'clock, the average effective power on brake was 50·86 horse-power, that is, a total of 310·70 horse-power hours, or an average of 51·783 H.P. for six hours.

The total consumption of fuel, coal and coke together, in six hours is 237·5 kilogrammes, or an average of 39·582 kilogrammes per hour.

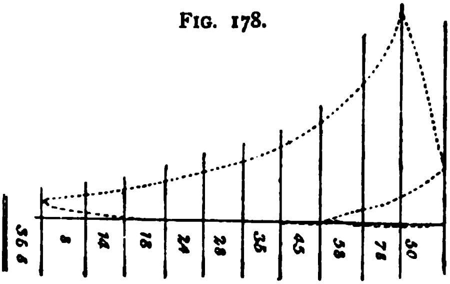
Therefore, the consumption of fuel per brake horse-power per hour is $\frac{39 \cdot 582}{51 \cdot 783} = 0 \cdot 7644$ kilogrammes, that is, the same as $\cdot 7644 \times 2 \cdot 2 = 1 \cdot 68$ lb. Of this total consumption per horse-power per hour,

Anthracite used in generator is 0·677 kg. × 2·2 = 1·49 lb.
Gas coke „ for boiler „ 0·0869 kg. × 2·2 = 0·19 lb.

The mean pressure of the steam = 3·65 atmospheres; and the consumption of steam for feeding the boiler and generating the gas is 0·54 kg., that is, 11·88 lb. per horse-power per hour, i. e. 6·22 times the amount of coke consumed beneath the boiler.

10. At the Wimborne Minster Waterworks, Dorset, a 6 horse-power nominal Atkinson "Cycle" gas engine, working a double-acting pump direct, is driven by Dowson gas. The yield of Dowson gas is 70 cubic feet per lb. of coal. In this gas engine the diameter of cylinder is 9½ inches, and the working stroke $11\frac{5}{16}$ in.

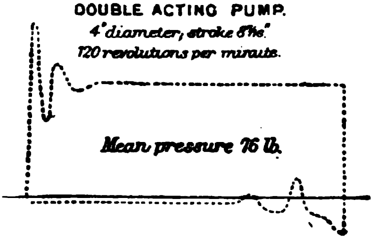
FIG. 178.



INDICATOR DIAGRAM FROM ENGINE CYLINDER.

In a preliminary trial made for five hours, the engine speed throughout was 120 revolutions per minute, and the consumption of Dowson gas 542 cubic feet per hour, the engine only taking 96 ignitions per minute. The engine indicator diagram (Fig. 178) was taken at the same time as the diagram (Fig. 179), from the pump working at its full capacity, 5122 gallons of water being forced through a 6-inch rising main 816 yards long, and the total lift of the water 171 feet.

[Fig. 179.



Indicator Diagram (Pump).

Find the indicated horse-power (*a*) in engine and (*b*) in pump, and, taking the actual horse-power in water lifted as 4·5, calculate the Dowson gas and equivalent coal consumption per hour, (*c*) per indicated horse-power in engine, and (*d*) per actual horse-power in water lifted.

*Answer.*—(*a*) The indicated horse-power in engine worked out from diagram, taking 96 ignitions per minute, is 6·96 horse-power, and (*b*) indicated horse-power in pump, at 120 revolutions per minute, is 4·54 horse-power; (*c*) Dowson gas consumption per hour per indicated horse-power in engine is 77·9 cubic feet, equivalent to 1·11 lb. of coal, and (*d*) the consumption per hour per actual horse-power in water lifted, is 120·4 cubic feet Dowson gas, or 1·72 lb. of coal. The combined efficiency of engine and pump is 63·46 per cent.

11. An Atkinson "Cycle" gas engine, tested by a Committee of the Franklin Institute, at Philadelphia, gave the following figures: Engine speed 118·26 revolutions per minute with a net load of 131·09 lb. on brake, and the effective circumference of brake-wheel 18·26 feet; the consumption of gas was 192·8 cubic feet per hour, and the water flowing

round and away from the water-jacket at the rate of 1 gallon per minute is raised 62·4° F.

Assuming that Philadelphia gas gives 628·7 heat units (lb. degree F.) per cubic foot when thoroughly burned, calculate (*a*) the consumption of gas per brake horse-power per hour; also find the distribution of heat, i.e. the proportions of the total amount of heat (*b*) turned into effective work, (*c*) spent in heating the water passing round the cylinder, and (*d*) rejected with waste gases by exhaust, together with that lost by radiation and convection to the atmosphere, as well as by friction in the mechanism.

*Answer.*—(*a*) The effective power as measured on the brake is $\frac{131 \cdot 09 \times 18 \cdot 26 \times 118 \cdot 26}{33{,}000} = 8 \cdot 6$ H.P.

Therefore the consumption of gas is $\frac{192 \cdot 8}{8 \cdot 6} = 22 \cdot 3$ *cubic feet per brake horse-power per hour.*

**Distribution of heat:**

Total amount of heat by burning

$\frac{192 \cdot 8}{60}$, or 3·213 cubic feet of gas per minute,

$3 \cdot 213 \times 628 \cdot 7 \times 772$ ... $= 1{,}559{,}450$ ft. lb.

Work done on brake per minute,

$131 \cdot 09 \times 18 \cdot 26 \times 118 \cdot 26 = 283{,}079$ „

Heating water 10 lb. per minute,

$10 \times 62 \cdot 4 \times 772$ ... ... $= 481{,}728$ „

Therefore the total heat is accounted for as follows:—

| | Per cent. |
|---|---|
| (*b*) Effective work done on brake ... ... | 18·152 |
| (*c*) Waste in heating jacket-water ... ... | 30·891 |
| (*d*) Lost by exhaust gases, radiation and convection, friction. (The balance of the *heat account* calculated by difference) ... | 50·957 |
| | 100·000 |

# CHAPTER XIV.

## LAWS OF GASES.

### Boyle's Law.

A QUANTITY of gas can be made to occupy a very small space in a cylinder, and it has also the property of expanding to any volume, however large, as the pressure on the piston is diminished and the temperature increased. It is, therefore, necessary to specify the *pressure*, *volume*, and *temperature* when considering the changes in a given mass of gas.

In 1662 Robert Boyle published the experimental fact, known as BOYLE'S LAW, or sometimes, in France, as Mariotte's law, that—

*When the temperature is kept constant, the volume of a given quantity of gas varies inversely as its pressure or elastic force, that is to say, the product of pressure and volume is constant.*

This is not absolutely true for any gas, but as gases are heated *above the critical temperatures*, below which they liquefy, they approach more and more closely to this imaginary state of a *perfect gas* which would exactly fulfil the law. At ordinary temperatures such gases as hydrogen and oxygen very nearly obey the law, when highly rarefied; on the other hand, compression and low temperatures, which tend to bring them to the liquid state, produce further deviation from this behaviour of the perfect gas.

According to Boyle's law, when a given mass of a perfect gas, kept at a fixed temperature, is allowed to expand, the product,

$$\textit{pressure} \times \textit{volume} = \textit{constant},$$

taking the pressure above a perfect vacuum, and the total volume occupied by the gas.

It follows that if we once know the volume and pressure of a definite quantity of gas, then, no matter how these alter, given one of them, we can readily find the other, provided the temperature remains the same.

In the gas engine cylinder, let the pressure of the fluid filling the space behind the piston be $p$ lb. per square inch measured from perfect vacuum. Suppose the diameter of the cylinder to be $d$ inches, then the cross sectional area of the piston is $\frac{\pi d^2}{4} = \cdot 7854 d^2 = a$ square inches (say). There is a pressure of $p$ lb. on every square inch, and, therefore, on the effective area $a$ square inches of piston, the total pressure is $p\,a$ lb. We shall express the volume occupied by the fluid in lengths of cylinder of uniform sectional area. The clearance and spaces in the cylinder, behind the piston, are considerable in a gas engine. These we ascertain, and represent the cylinder a little longer in order to take into account the volume of such passages, and express the total volume in terms of length of cylinder, of which the uniform sectional area is $a$ square inches, or $\frac{a}{144}$ square feet. The volume of gas contained in length $l$ feet of this cylinder would be $\frac{a\,l}{144}$ cubic feet, so that the product

$$\textit{pressure} \times \textit{volume} = \frac{p\,a\,l}{144}.$$

But $\frac{a}{144}$ is always the same for any one cylinder, therefore, Boyle's law becomes,

$$p\,l = \text{constant}.$$

If we know the pressure when the working fluid occupies a certain length of the cylinder, we can find by this formula what the pressure is when the piston has been moved through a given distance, provided the temperature is the same as at first.

For example, if the pressure is 80 lb. per square inch when the piston is 1·2 feet from the end of cylinder, what is the pressure of the same mass of gas at the same temperature when the piston is 2 feet from the end of cylinder?

Here $80 \times 1\cdot2 = p \times 2$, since both products are equal to the same constant, therefore $p = 48$ lb. per square inch.
—*Answer.*

This law makes calculation very simple. To represent it graphically, for a given mass of gas, we plot on a sheet of squared paper a number of values of the pressure $p$ and of the corresponding lengths $l$ feet of the cylinder or volumes $v$ in cubic feet occupied by the gas.

*Example.*—A perfect gas occupies 4 cubic feet under a pressure of 60 lb. per square inch; what is its volume $v$ under a pressure of 30 lb. per square inch, at the same temperature?

Here,

$$60 \times 4 = 30 \times v;$$

therefore,

$$v = 8 \text{ cubic feet.—}\textit{Answer.}$$

Now one cubic foot of a perfect gas, under a pressure of 20 lb. per square inch, will occupy a volume of 2 cubic feet when the pressure becomes 10 lb. per square inch, at the same temperature.

In this case $pv = 20.$

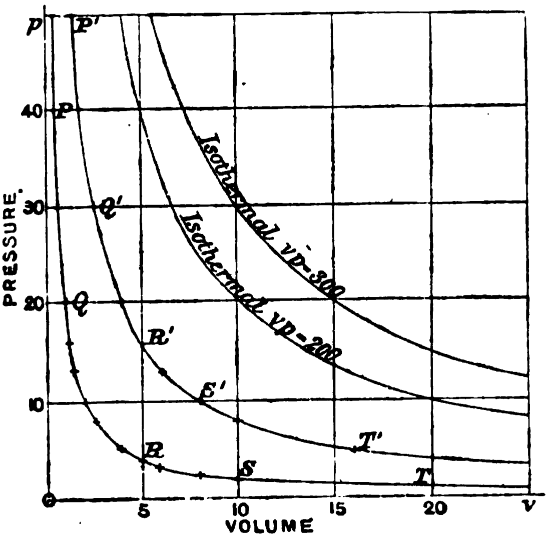
By splitting up 20 into factors we may find any number of corresponding values for $p$ and $v$. If we tabulate these values, and take a sheet of squared paper, we can represent the law connecting the pressure and volume at constant temperature by a curve such as would be traced by the pencil of an indicator attached to an engine cylinder.

Take the following factors of 20:—

| $v$ Volume in Cubic Feet. | $p$ Pressure in lb. per Square Inch. | $v$ Volume in Cubic Feet. | $p$ Pressure in lb. per Square Inch. |
|---|---|---|---|
| 0 | ∞ | 5 | 4 |
| 0·5 | 40 | 10 | 2 |
| 1 | 20 | 15 | $1\cdot\dot{3}$ |
| 1·5 | $13\cdot\dot{3}$ | 20 | 1 |
| 2 | 10 | 25 | 0·8 |
| 2·5 | 8 | ∞ | 0 |
| 4 | 5 | | |

We may employ any scale we please to represent these values, in the most convenient way, on our sheet of squared paper, Fig. 180. Let horizontal distances represent volumes, or lengths along cylinder; and vertical distances, pressures.

FIG. 180.



Now, laying off half a division horizontally, and counting up 40 of the equal vertical divisions, we find the first point P, which we mark by a little cross; then measuring one division horizontally, and 20 vertically, we get another point Q, and in this way we can mark all the values.

Each point represents the fact that the given mass of gas when occupying that volume will exert the corresponding pressure, the temperature being still the same. For instance, the point S shows that when the volume is 10 cubic feet, the gas exerts a pressure of 2 lb. per square inch. Now, as we take a greater and greater number of these points, P, Q, R, S, T, we remark that they all lie along a regular curve, which gradually approaches the lines O *v* and O*p*, but never touches either of these lines, except at an infinite distance.

This curve tells us at a glance the relation between simultaneous values of $p$ and $v$ of the given mass of gas *when the temperature remains constant.* On this account it is called an *isothermal* curve, from two Greek words signifying "*equal temperature.*" From the fact that $pv$ is constant, we know that the curve is a rectangular *hyperbola,* of which O$v$ and O$p$ are the asymptotes. A hyperbola is the trace on the surface of a right cone made by a plane cutting the cone parallel to its axis. Knowing the properties of this curve we are enabled to find the area bounded by any part of it and the asymptotes, and hence have the work done by the gas in expanding from one volume to another under constant temperature (see page 241).

For a different temperature there will be another similar isothermal curve. Suppose we heat the same quantity of gas, to start with, until it occupies 4 cubic feet under a pressure of 20 lb. per square inch at the new temperature. In this case the product $p\,v$ is 20 × 4, or 80. If we split this into factors and plot the different values as before, we get the isothermal P′ Q′ R′ S′ T′ (Fig. 180) for the given mass of gas at the new temperature.

In this way we can draw any number of isothermals for the same mass of gas, by taking different temperatures, as is shown in Fig. 180. If we trace them for equal intervals of temperature, we find they approach one another more closely as the temperature becomes higher.

Suppose the temperatures to be 1° C. apart, and we trace an isothermal line for the same quantity of gas at each temperature. Now imagine these isothermal curves held above the paper, parallel to their former positions, the perpendicular distance of each above the plane of the paper representing its absolute temperature, a surface containing all the isothermals so arrayed will determine, by the three ordinates of any point on it, the relations between the pressure, volume, and temperature of the given mass of gas. Hence, if we are given a model of this *characteristic surface* for a mass of gas, with all the isothermals traced thereon, we can at once determine its pressure, volume, and temperature when any two of these are known.

This surface may be compared to a hollow up a hillside; the isothermals correspond to *contour lines*, the absolute temperatures being the levels or heights.

## Law of Charles.

In 1787 the experiments of Charles showed that different gases, when kept at constant pressure and heated, had all practically the same coefficient of expansion.

Subsequently Gay Lussac determined this coefficient for gases heated and kept at constant pressure, as well as that for the increase of pressure at constant volume, and still more exact values of the same coefficients were obtained by Regnault in his classic investigations, which fully established the LAW OF CHARLES :—

*All gases expand* $\frac{1}{273}$*rd of their volume at* 0° C. *for an increase in temperature of* 1° C. *when heated under constant pressure.*

Experiment shows that the more highly rarefied a gas becomes, and the further removed above its critical temperature of liquefaction, whilst the constant pressure is kept very small, so that the particles of the gas have free play and are comparatively far apart, the more nearly does the gas follow this simple law.

For practical purposes we may take the dilatation of equal volumes of all gases the same for equal increments of temperature :—

Thus 273 cubic feet of any gas at 0° C. become 274 cubic feet at 1° C., 275 at 2° C., and generally $273 + t$ cubic feet at $t^\circ$ C. This fraction $\frac{1}{273}$ or ·00367 is called the coefficient of expansion of gases. One cubic foot of a gas at 0° C., becomes, under *constant pressure*, 1·00367 cubic feet at 1° C., $1 + \cdot 00367 \times 2$, that is, 1·00734 cubic feet at 2° C., and $1 + \cdot 00367 \times t$ at $t^\circ$ C.

In a more general form the law holds that, under *constant pressure*

$$v_t = v_0(1 + \cdot 00367 \times t),$$

where $v_0$ denotes the volume of the gas at 0° C., and $v_t$ its volume at $t$° C.

It follows that,

$$\frac{v}{v_1} = \frac{1 + \cdot 00367 \times t}{1 + \cdot 00367 \times t_1} = \frac{273 + t}{273 + t_1},$$

where $v$ stands for the volume at temperature $t$° C., and $v_1$ at $t_1$° C., for the gas kept at constant pressure.

But if $p$ and $p_1$ are the respective pressures, BOYLE'S LAW tells us that the volumes vary inversely as the pressures, and,

$$\frac{v}{v_1} = \frac{273 + t}{273 + t_1} \times \frac{p_1}{p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Again, in the third case, when the **volume** of a gas is kept constant, and the temperature increased, the law holds

$$p_t = p_0\left(1 + \frac{1}{273} \times t\right), \text{ or } \qquad \frac{p_t}{p_0} = \frac{273 + t}{273},$$

where $p_0$ denotes the pressure at 0° C., and $p_t$ the pressure at $t$° C.

Take $t = 273$° C., and we have

$$p_{273} = p_0\left(1 + \frac{1}{273} \times 273\right) = 2p_0;$$

thus, at 273° C., the pressure of a given mass of gas is double what it was at 0° C., the *volume being the same.* On the other hand, when the temperature falls, while the volume is kept constant, the pressure gets less. At − 273° C., if the gas remained at constant volume, the pressure would be

$$p_{-273} = p_0\left(1 - \frac{1}{273} \times 273\right),$$

therefore

$$p_{-273} = 0.$$

Hence at this temperature the pressure or elastic force of the gas is zero, that is, the particles are at rest, and the gas is entirely deprived of heat. Obviously, such a temperature cannot be practically maintained during any appreciable time, because the gas and containing vessel would receive heat from surrounding bodies, and if it were possible to get such an extreme degree of cold, the coefficient $\frac{1}{273}$ would not remain constant, and the gas would change its physical state to the liquid or solid.

This – 273° C. is called the **absolute zero** point, and forms the basis of an *absolute scale of temperature.*

Ordinary readings on the Centigrade scale are changed into absolute temperatures, reckoned from this new zero, by adding 273. Readings on the Fahrenheit scale may be converted into absolute temperatures by adding 459·4, or about 460.

Taking the large letter T to denote absolute temperature, and small $t$ the ordinary temperature in Centigrade degrees, we have

$$T = t + 273.$$

The law connecting the pressure and temperature of a gas, at *constant volume,* becomes

$$\frac{p}{p_0} = \frac{T}{T_0},$$

that is, *the pressure varies directly as the absolute temperature, and serves to determine it.* We can by this rule find the temperature of a gaseous mixture in the cylinder of the combustion engine from its observed pressure at constant volume.

It is always found that when any explosive mixture of gas and air is fired, the pressure produced falls far short, being only about one-half of what should be expected by this law if the total heat of combustion were evolved at the instant of explosion. In fact, slow or retarded combustion takes place with *gradual* evolution of heat. It follows that the small contraction (p. 370), due to the complete combustion of a dilute mixture of coal-gas and air, does not all occur at the first instant of explosion; and, for practical purposes, the working fluid in the internal combustion engine cylinder behaves like a perfect gas which receives heat from little furnaces inside the gas itself.

We may also write the above equation (1) in the simple form

$$\frac{v}{v_1} = \frac{\mathrm{T} p_1}{\mathrm{T}_1 p},$$

or,

$$\frac{p\,v}{\mathrm{T}} = \frac{p_1 v_1}{\mathrm{T}_1}.$$

Thus $\frac{p\,v}{\mathrm{T}}$ is always the same for a given mass of gas, where $p$ stands for the pressure above vacuum, $v$ the volume, and T the absolute temperature.

Hence the LAW OF CHARLES, combined with that of BOYLE, gives this **simple general law** connecting the pressure, volume, and temperature of the ideal perfect gas, expressed by the *characteristic equation*:—

$$\frac{p\,v}{\mathrm{T}} = \text{constant}.$$

If we know the pressure, volume, and absolute temperature of a quantity of gas, this quotient never alters, however the pressure, volume, and temperature may alter; and, given any two of these, the other can be readily determined.

*Example* 1.—A given mass of gas occupies 10 cubic feet under an absolute pressure of 30 lb. per square inch at 27° C. What pressure $p$ will the gas exert when the volume becomes 5 cubic feet, and the temperature 227° C.?

Add 273° to the temperatures, to convert them into absolute temperatures, and substitute the values in the characteristic equation.

Thus,

$$\frac{p\,v}{\mathrm{T}} = \frac{30 \times 10}{273 + 27} = \frac{5\,p}{273 + 227},$$

so that,

$$p = \frac{30 \times 10 \times 500}{5 \times 300} = 100 \text{ lb. per square inch.}$$

—*Answer.*

*Example* 2.—In an internal combustion engine cylinder, 6 cubic feet of the working fluid at 120° C., and pressure of 15 lb. per square inch above vacuum, is compressed to 3 cubic feet, and pressure 42 lb. per square inch. What is the new temperature?

Putting these values in our equation, we have

$$\frac{15 \times 6}{273 + 120} = \frac{42 \times 3}{T},$$

that is,

$$T = \frac{393 \times 42 \times 3}{15 \times 6} = 550 \cdot 2.$$

Hence the temperature is 550·2 – 273, or 277·2 C.

## Isentropic or Adiabatic Curves.

When a gas expands, *doing external work* solely at the expense of its own intrinsic energy, *without receiving heat* from other bodies or giving heat to them, the expansion is said to be **adiabatic**, and the law connecting the pressure and volume is

$$p v^{\gamma} = \text{constant},$$

where $\gamma$ stands for the ratio of the specific heats of the gas at constant pressure and at constant volume.

We have seen that in the case of air $\gamma$ is 1·408, and when air expands or is compressed *without gain or loss of heat*, the adiabatic or isentropic law is

$$p v^{1 \cdot 408} = \text{constant}.$$

If we take, for example, 8 cubic feet of air under a pressure of 25 lb. per square inch, we have

$$25 \times 8^{1 \cdot 408} = \text{a constant, } k \text{ (say)},$$

and taking logarithms

$$\log 25 + 1 \cdot 408 \log 8 = \log k,$$

so that

$$k = 467 \cdot 18,$$

and for this quantity of air the adiabatic law becomes

$$p v^{1 \cdot 408} = 467 \cdot 18.$$

Now take logarithms, and we see the relation holds

$$\log p + 1 \cdot 408 \log v = \log 467 \cdot 18,$$

whence

$$\log p = \log 467 \cdot 18 - 1 \cdot 408 \log v.$$

Give different values to $v$ in this equation, and we can calculate the corresponding values of $p$ given in the table:—

| $v$. | $p$. | $v$. | $p$. |
|---|---|---|---|
| 5 | 48·5 | 9 | 21·2 |
| 6 | 37·5 | 10 | 9·4 |
| 7 | 30·2 | 20 | 6·9 |
| 7·5 | 27·4 | 24 | 5·3 |
| 8 | 25·0 | | |

Plotting these results on squared paper, as in Fig. 181, we get the curve $Q^1$ P $R^1$.

The point P represents the initial state of the given quantity of air occupying 8 cubic feet under pressure of 25 lb. per square inch. Now, if instead of allowing the air to expand at the expense of its own heat, which is converted into work, causing its temperature to fall, we were to heat the air so as to maintain its temperature constant, then it would follow the isothermal law,

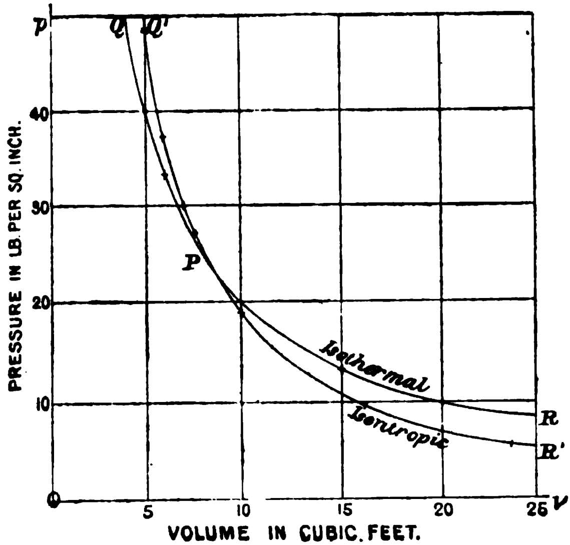
$$p v = 25 \times 8, \text{ or } 200.$$

Split 200 into a great number of different factors and plot the values of $v$ and $p$ in each, we get the isothermal line P Q R which crosses the adiabatic at the point P.

We remark that both curves are asymptotic to the line O $v$, but the adiabatic is steeper than the isothermal.

The characteristic of the *isothermal* curve is that the *temperature* $t$ remains constant, whereas during the *rapid*

Fig. 181.

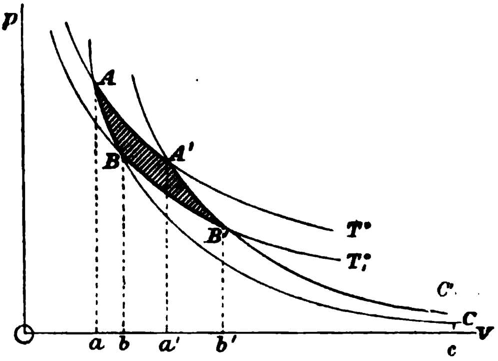


*adiabatic operation* the *entropy* $\phi$ of a given amount of gas is that which remains constant when the gas neither gains nor loses heat; but the entropy increases or diminishes as heat enters or leaves the gas. According as a body gains or loses heat H at constant absolute temperature T, we say its entropy $\phi$ is increased or diminished by $\frac{H}{T}$, so that H the change in **heat-energy** is the product of the *two* factors, temperature T and entropy $\phi$, that is, $H = T\phi$. In other words, heat-energy equals "thermal height" multiplied by "thermal weight."

To get a more general idea of some properties of adiabatics, let a quantity of gas be enclosed in a cylinder fitted with a piston. Imagine the cylinder and piston to be perfect non-conductors, which neither take up any heat themselves nor allow heat to pass through them to or from the gas. It is impossible to make such a cylinder, because heat can pass through all bodies. Hence adiabatic lines can only be drawn approximately from the results of direct experiment, from which, however, we can calculate their form for any particular substance.

To start with, let the point A, Fig. 182, represent the state of the gas occupying volume O *a*, under a pressure A *a*, at the absolute temperature T°.

FIG. 182.



Now, if the gas be allowed to expand, doing external work by pushing forward the piston, without receiving heat, its temperature and pressure fall, since the work has been done at the expense of the molecular kinetic energy of the gas. The pressure corresponding to any volume will then be less than if the gas had been heated to maintain its temperature constant during the expansion, hence the isentropic line A B C through the point A crosses the isothermal line or hyperbola and falls below it, being steeper or more inclined to the axis O *v* than is the corresponding isothermal A A' T° through the same point A.

The same thing is seen for compression. If the piston be pushed inwards, the pressure, already increased by ordinary isothermal compression at constant temperature, will be still further increased, since the work spent in compression generates heat, which is not allowed to escape through the walls of the cylinder, but causes a greater increase to the temperature and pressure of the gas. Thus, if the co-ordinates of the point B′ represent the volume and pressure of the given quantity of gas at absolute temperature $T_1°$, when the gas is compressed by pushing the piston into the cylinder and the heat developed is allowed to escape so that the gas is kept at constant temperature, the pressure will rise along the isothermal B B′ $T_1°$. On the other hand, if the walls of the cylinder be perfect non-conductors, so that the heat generated by compression cannot pass through them, but is retained, then the pressure will rise along the isentropic A′ B′ C′, the temperature of the gas also changing.

Let a given quantity of gas, originally in the state A, be allowed to expand along the isentropic A B C, pushing the piston, and thus doing external work without gain or loss of heat. The work done by the gas on the piston is represented by the area *c a* A B C, which represents the change in the intrinsic energy of the gas. The pressure gradually falls and becomes infinitely small as the isentropic A B C is continued, coming nearer and nearer, but still asymptotic to the line O $v$, as the volume becomes indefinitely great.

The molecular kinetic energy of the gas is gradually spent in doing work on the piston until both the temperature and pressure become zero. Then the gas is so highly rarefied and in the perfectly gaseous state that no appreciable work is done either in further expanding or slightly compressing it, that is, the molecules are very far apart as compared with their size. The gas, so far as we know or rather suppose, will then only possess *potential* energy of molecular separation, but we have no means of finding how much, and hence *cannot tell the total amount of energy stored up in a given quantity of gas*, or, in fact, in any body. We merely know how much energy it contains in the form of *sensible* heat, and this could all be converted into work only by infinite expansion, which is obviously beyond the limits of any cylinder, and practically impossible. However, it is obvious that the further a gas is allowed to expand, the more work can be got out of it, since at least some of the heat in it is in the form of kinetic energy.

At the same time we must bear in mind that, although we can measure and estimate the amounts of heat which go into a body or come out of it; yet as to the total amount of heat energy in it at any time we cannot even guess or form an exact idea until more is known about the ultimate structure of matter.

## STUDY OF INDICATOR DIAGRAM.

Professor Perry has pointed out a simple method of studying and deriving useful information from the gas engine indicator diagram.

When a fluid fills the space behind the piston in a cylinder, we can tell how much work is done on the piston throughout its stroke if we know how the pressure of the fluid alters as it drives the piston.

In all cases it is found that

$$p\,l^m = \text{constant}$$

is a good form for the law of expansion or compression, where $m$ ought to be known for the particular case. Thus $m = 1$ gives the isothermal curve, and $m = \gamma$ the isentropic curve.

*Example.*—The expansion curve of a gas engine indicator diagram has been corrected for the vibrations of the indicator spring, &c., and at two well-defined points of the curve we have the following values for $p$ the pressure in lb. per square inch above vacuum, and for $l$ the total length from end of cylinder including clearance:

When

$l_1 = 1$ foot, $p_1 = 80$ lb. per square inch;

and when

$l_2 = 3$ feet, $p_2 = 20$ " " " " .

**To find the law of the expansion curve,**

Assume

$$p\,l^x = \text{constant};$$

then

$$p_1\,l_1^x = p_2\,l_2^x = k;$$

that is,

$$80 \times 1^x = 20 \times 3^x;$$

whence

$$4 = 3^x;$$

taking logarithms we have

$$x \log 3 = \log 4$$

$$\therefore \qquad x = \frac{\log 4}{\log 3} = \frac{0 \cdot 6021}{0 \cdot 4771} = 1 \cdot 262.$$

so that

$$80 \times 1^{1 \cdot 262} = k, \quad \therefore \quad k = 80;$$

∴ the law of expansion of the fluid in this case is

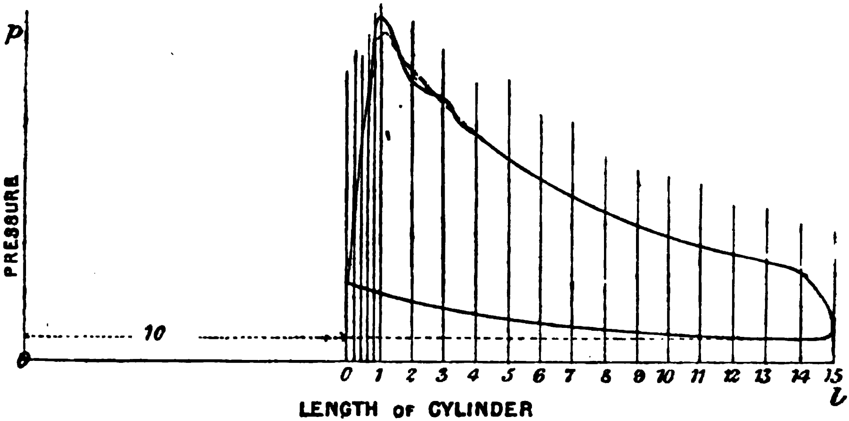
$$p\,l^{1 \cdot 262} = 80.$$

In this example the law of the expanding gas was determined from measurements of the co-ordinates of only two points on the indicator diagram, as engineers are in the habit of doing. We must bear in mind, however, that the position of either point may be greatly altered by the vibrations of the indicator-spring. This sinuous or wavy movement is specially noticeable in the early part of the expansion-curves of gas engine diagrams. Moreover, we have every reason to believe that the expansion part ought to have no sinuosities, and it is of the utmost importance to find some means of eliminating the effects produced by these vibrations of the indicator spring. This difficulty is partly overcome by the rule given at page 249. Still, the scale of the diagram is necessarily so small that it is often very difficult to make measurements of pressure to the fraction of a pound per square inch, and a slightly inexact reading may lead to a serious discrepancy in our law of expansion, which we cannot check if we only consider two points on the diagram.

It is obvious, then, we ought to take a great many points on the curve in order to determine the most probable values of the constants. This we can do most readily by the use of squared paper, which not only enables us to correct errors of observations, but also tells us at a glance whether our curve is the right and reasonable one.

The method can be best understood from a numerical example. We shall now proceed to find the law of expansion from the gas engine indicator diagram, shown in Fig. 183.

FIG. 183.



It is known that the clearance space is two-thirds the length of travel of piston. If $\lambda$ is the distance passed through by the piston from the end of its stroke, the stroke being $1\frac{1}{3}$ foot, then the clearance is 0·889 foot, and $\lambda + 0{\cdot}889 = l$ feet expresses the volume of the fluid at any instant. For the sake of convenience we shall divide $\lambda$ into 15 equal parts, then the clearance equals 10 of these, and at any point, $\lambda + 10 = l$ will be the volume of cylinder including clearance. The pressure $p$ is in lb. per square inch above vacuum, and equals the observed pressure above atmospheric line, together with 14·7. The dotted line at the top of the expansion curve on the diagram shows the correction made on account of the vibrations of the indicator spring.

The following are the measurements of $l$ and $p$ made on the expansion curve:—

| $\lambda$ | Observed Pressure above Atmospheric. | $p$ Above Vacuum $=$ observed $+ 14·7$ | Log $l$ $= \log(\lambda + 10)$. | Log $p$. |
|---|---|---|---|---|
| 0 | 30·5 | 45·2 | 1 | 1·6551 |
| 1 | 173·5 | 188·2 | 1·0414 | 2·2747 |
| 2 | 151·5 | 166·2 | 1·0792 | 2·2206 |
| 3 | 131·5 | 146·2 | 1·1139 | 2·1650 |
| 4 | 115·0 | 129·7 | 1·1461 | 2·1130 |
| 5 | 102·0 | 116·7 | 1·1761 | 2·0671 |
| 6 | 91·0 | 105·7 | 1·2041 | 2·0241 |
| 7 | 81·0 | 95·7 | 1·2304 | 1·9809 |
| 8 | 72·5 | 87·2 | 1·2553 | 1·9405 |
| 9 | 66·0 | 80·7 | 1·2788 | 1·9069 |
| 10 | 59·5 | 74·72 | 1·3010 | 1·8704 |
| 11 | 54·0 | 68·7 | 1·3222 | 1·8370 |
| 12 | 49·5 | 64·2 | 1·3424 | 1·8075 |
| 13 | 44 | 58·7 | 1·3617 | 1·7686 |
| 14 | 38 | 52·7 | 1·3802 | 1·7218 |
| 15 | — | — | — | — |

If we assume the law of the expansion curve to be of the form

$$p\,l^m = \text{constant } k;$$

taking logarithms we have

$$\log p + m \log l = \log k = \text{constant C (say).}$$

Now this is the equation of a right line, hence, when we plot all the corresponding values of log $p$ and log $l$ on squared paper as the co-ordinates of points, these points so found ought to lie in a straight line if our assumption is correct. It is obvious that the points so found, Fig. 184, do lie fairly well in a straight line when we take our measurements from the part of the expansion curve before the exhaust valve opens to allow the gases to escape. We allow for slight errors of observation by finding **what line lies most evenly among the points.** This we can do by means

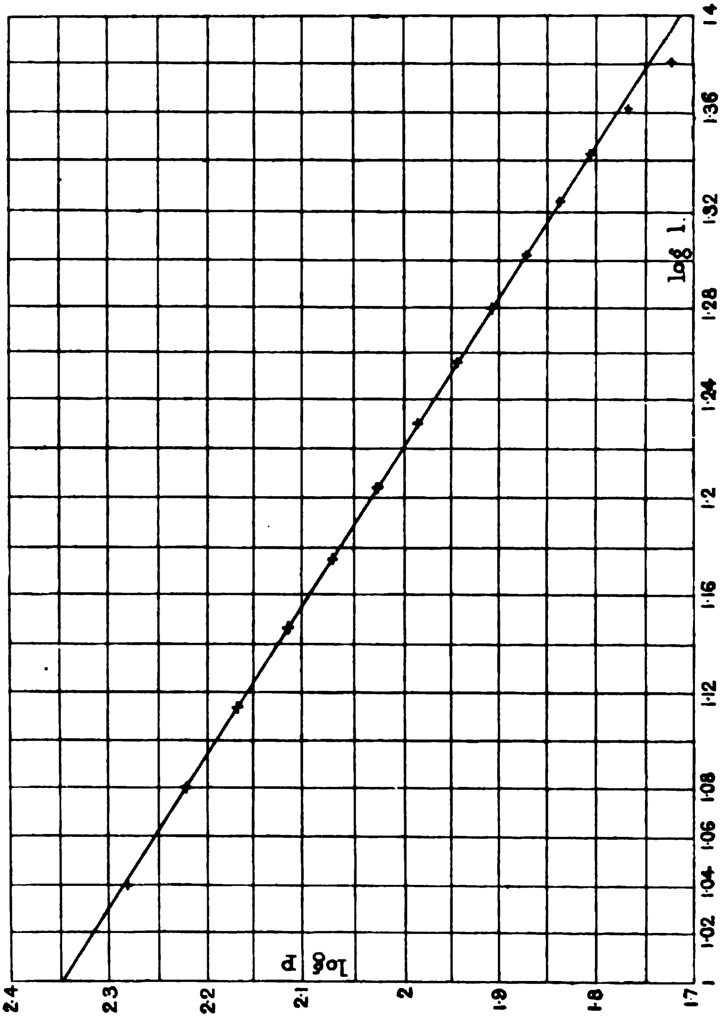


Fig. 184.

of a fine thread stretched over the points. If we have any doubt about the line following some simple curve, we can calculate other values and find an extra number of points at the doubtful parts of the line, which we can thus fill in by interpolation. When we hold the thread in such a position as to pass between most of the points and to indicate the true direction of the required line, mark the extreme points through which the thread passes and then draw the line with a straight-edge or ruler. This line tells us at once the relation or law connecting log $p$ and log $l$. For, taking two points on the line, we find

when

$$\log l = 1\cdot346,\ \log p = 1\cdot8\ ;$$

and when

$$\log l = 1\cdot028,\ \log p = 2\cdot3.$$

Substituting these values in the above equation gives

$$1\cdot8 + 1\cdot346\,m = \text{C or } \log k,$$

and

$$2\cdot3 + 1\cdot028\,m = \text{C} \;,,\;\; ,,\;\; ,,\,;$$

subtracting, we have

$$\cdot318\,m = \cdot5,$$

$$\therefore\quad m = \frac{\cdot5}{\cdot318} = 1\cdot572.$$

This gives us $1\cdot8 + 1\cdot346 \times 1\cdot572 = \log k$,

and $2\cdot3 + 1\cdot028 \times 1\cdot572 = \log k$;

whence,

$$\log k = 3\cdot9160, \text{ take antilogarithm,}$$

$$\therefore\ k = 8240.$$

Hence the **law of expansion** is

$$p\,l^{1\cdot572} = 8240 \;.\;.\;.\;.\;.\;.\;.\;.\quad (1)$$

In the same way we find the law for the compression part of the diagram is

$$p\,l^{1\cdot25} = 798 \;.\;.\;.\;.\;\;\;.\;.\quad (2)$$

Now $\gamma$, the ratio of the specific heats of the gaseous mixture in the cylinder behind the piston, is about 1·37, so that the equation of the isentropic curve is

$$p\,l^{1\cdot 37} = \text{constant.}$$

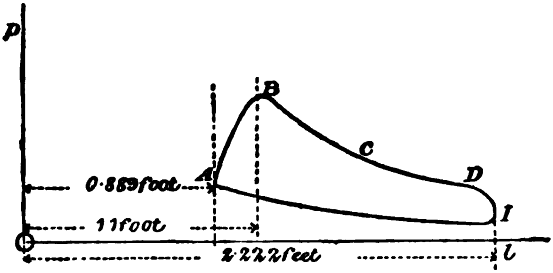
It is obvious then that the expansion curve (1) in this indicator diagram is steeper than the isentropic; but the compression curve (2) has a more gradual slope and lies between the isentropic and isothermal curves. We know that for the isentropic law the gas expands without loss or gain of heat, whilst for isothermal expansion heat is received to keep up constant temperature. In the gas engine cylinder there is combustion going on, and the gas loses heat by conduction through the cylinder walls to the jacket water, as well as that spent in the cylinder driving the piston. When the *curve is steeper than an isentropic*, as in the expansion (1), the mixture is on the whole losing more heat than is being generated by its combustion; on the other hand in the compression part (2) the mixture gains heat from the piston and cylinder.

## TEMPERATURE CURVE FROM INDICATOR DIAGRAM.

A dilute mixture of coal gas and air, when compressed and burned in the gas engine cylinder, suffers so small a diminution in volume when reduced to the original temperature and pressure, that we may practically regard this working fluid as a perfect gas which receives heat from a great number of little internal furnaces and follows the law $\frac{p\,l}{T} = \text{constant}$. Moreover, the mass of stuff enclosed in the cylinder remains the same from admission of charge till exhaust, so that if the pressure volume and temperature be known for one position, we can by this formula find the temperatures of the mixture at every other point on the indicator diagram (Fig. 185) from I along the curve A B C right round to D, where the exhaust valve opens and allows the burnt products to escape.

At I (Fig. 185) we have a fresh charge of gas and air, at say 10° C., together with the products of previous combustions at 400° C. Taking weights of constituent gases and average specific heat, the temperature of the mixture is calculated to be about 123° C. Here the absolute pressure $p$ is ordinary atmospheric, or 14·7 lb. per square inch above vacuum; and the total length of cylinder (including clearance space) occupied by the mixture is 2·222 feet.

FIG. 185.



Thus at I, $l = 2\cdot222$ ft., $p = 14\cdot7$ lb. per square inch, and $T = 123° + 273° = 396°$. After making corrections on the diagram for vibrations of indicator spring, the values of $p$ are found by careful measurements on the curve I A B C D, for the various values of $l$. At the point B, $l = 1\cdot1$ ft., and $p = 126\cdot4$ lb. per square inch.

To **find the temperature** at this point we have then for $\frac{p\,l}{T}$ the following terms given:—

$$\frac{14\cdot7 \times 2\cdot222}{396} = \frac{126\cdot4 \times 1\cdot1}{T},$$

hence,

$$T = \frac{396 \times 126\cdot4 \times 1\cdot1}{14\cdot7 \times 2\cdot222} = 1686° \text{ absolute.}$$

This gives us the temperature 1686 − 273, or 1413° C.

—*Answer.*

In this way the temperatures have been calculated from another indicator diagram (Fig. 186) I A B C D, assuming the temperature to be 120° C. at I, just before compression begins:

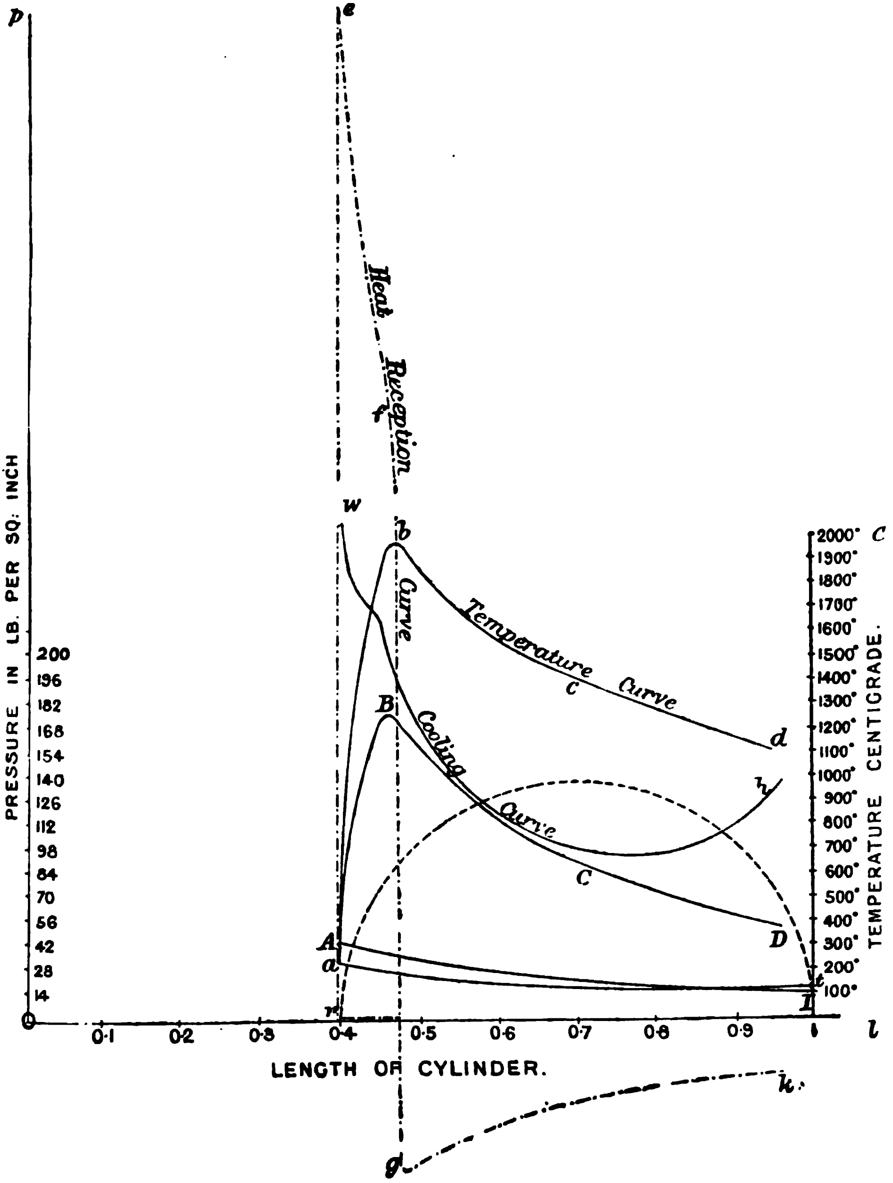
| Length of Cylinder (including clearance) Feet. | Pressure above Vacuum in lb. per Square Inch. | Temperature of Fluid $t°$ C. | $t°$ − 60° C. |
|---|---|---|---|
| 1 | 14·5 | 120 | 60 |
| ·9 | 15·0 | 95 | 35 |
| ·8 | 17·4 | 103 | 43 |
| ·7 | 21·3 | 130 | 70 |
| ·6 | 26·3 | 154 | 94 |
| ·5 | 34·0 | 189 | 129 |
| ·4 | 47·0 | 236 | 176 |
| ·45 | 173·6 | 1840 | 1780 |
| ·475 | 173·6 | 1958 | 1898 |
| ·5 | 157·4 | 1856 | 1796 |
| ·55 | 131·6 | 1685 | 1625 |
| ·6 | 114·2 | 1582 | 1522 |
| ·7 | 90·2 | 1425 | 1365 |
| ·8 | 72·8 | 1303 | 1243 |
| ·9 | 60·0 | 1186 | 1126 |
| ·95 | 53·8 | 1108 | 1048 |

Plotting the temperatures of the fluid as ordinates at the various points, we obtain *t a b c d*, the **temperature curve.**

The temperature of the water jacket and cold cylinder walls being 60° C., assume that the *rate of loss* of heat from the stuff to the cylinder is proportional to the excess of its temperature, that is, to $t - 60°$ C.

The rate of cooling increases more rapidly than this excess at high temperatures, and there is greater loss at higher pressures between the hot gaseous fluid and the cold cylinder walls. Again, the piston moves more quickly about the middle of its stroke than at the ends. The motion of piston is nearly a simple harmonic motion, proportional to the ordinates of the semicircle described with diameter equal to the length of stroke.

FIG. 186.


p
e
Heat Reception
f
w
b
Curve
Temperature Curve
c
d
B
Cooling Curve
h
C
D
A
a
t
n
I
g
k
l
PRESSURE IN LB. PER SQ: INCH
200
196
182
168
154
140
126
112
98
84
70
56
42
28
14
O
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1
LENGTH OF CYLINDER.
2000° C
1900°
1800°
1700°
1600°
1500°
1400°
1300°
1200°
1100°
1000°
900°
800°
700°
600°
500°
400°
300°
200°
100°
TEMPERATURE CENTIGRADE.

Let H be the quantity of heat lost by the fluid to the cylinder walls during the short interval of time $\tau$, then $\frac{\mathrm{H}}{\tau}$, the rate of loss of heat per second, is proportional to the excess of temperature $t - 60°$ C.

The velocity of the piston at any point, $\frac{l}{\tau}$ is proportional to the ordinate of the semicircle; so that

$$\frac{\mathrm{H}}{\tau} \div \frac{l}{\tau} = \frac{\mathrm{H}}{l}$$

is the rate of loss of heat by the stuff to the cold walls of the cylinder at that point, per foot travel or unit volume swept through by the piston.

Hence the simple rule, to find the rates at which the working fluid gives up heat to the cylinder walls per foot of the piston-travel at the different parts of the curve: *divide the excess temperature by the piston velocity or ordinates of the semicircle at each point, and the quotients will be the ordinates of the* **cooling curve.**

Since the **pressure** $p$, in pounds per square inch, taken from the indicator diagram, is the **rate at which work is being done** by the working fluid on the piston per foot travel or unit volume moved through, in the same way $q$ represents the *rate at which the fluid shows that it is receiving heat* to do that work, for every point of the curve.

Let $dp$ be the increase in the pressure while the piston moves through a very short length of stroke $dl$, then clearly the value of $\frac{dp}{dl}$ is the rate at which the pressure is increasing, at the point corresponding to the mean value of $l$, as the piston moves along the cylinder. If the pressure diminishes, this will be negative.

Now we know from thermodynamics how to find $q$, the ordinate of the **heat reception curve**, since,

$$q = \frac{1}{\gamma - 1}\left(\gamma p + l\frac{dp}{dl}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where $\gamma$ is 1·37 for the fluid during combustion, this expression becomes

$$q = \frac{1}{0 \cdot 37}\left(1 \cdot 37\, p + l\,\frac{dp}{dl}\right) \quad . \quad . \quad . \quad . \quad (2)$$

From this formula, and the indicator diagram A B C D, $q$ may be found by three methods.

*First Method.*—Take careful measurements of the values of $p$, corresponding to many values of $l$ including clearance, along the curve A B C D. Calculate the small increase $dp$ corresponding to the small change $dl$, from one position to the next, and the quotient is the mean value of the symbol $\frac{dp}{dl}$ for the mean $l$ between the two positions. Substitute these numbers in equation (2), and so obtain $q$ the ordinate of the *heat reception curve e f g h.*

The fluid receives heat so rapidly at the ignition point A that this curve is given broken in Fig. 186, where the area between *e f g h*, the line O *l*, and any two ordinates represents in foot-pounds the **heat energy given to the fluid,** to the same scale as that of the indicator diagram which gives the work done on the piston between these two positions.

*Second Method.*—Since the expansion and compression parts of the indicator curve follow the law

$$p\, l^m = \text{constant, or } p = k\, l^{-m},$$

we may obtain the value of $\frac{dp}{dl}$ by actual differentiation, and reduce equation (1) to the form

$$q = \frac{\gamma - m}{\gamma - 1}\, p \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

By means of this equation it is an easy matter to calculate $q$ for the various parts of the stroke.

Thus, for the expansion part of the indicator curve, Fig. 186, $\gamma = 1 \cdot 37$ and $m = 1 \cdot 553$, then

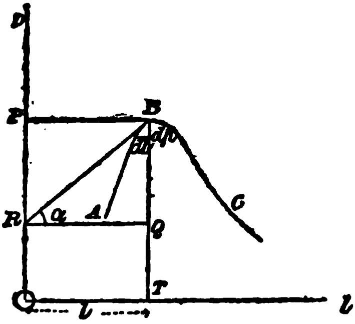
$$q = \frac{1 \cdot 37 - 1 \cdot 553}{1 \cdot 37 - 1}\, p; \quad \text{or,} \quad q = -\,0 \cdot 494\, p.$$

The negative sign shows that the fluid is cooling.

*Third Method.*—For a point B on the explosion part of stroke, $q$ may be found by the tangent method.

At the point B, draw a tangent B R to the indicator curve A B C, Fig. 187, meeting the line O $p$ in R. Draw R Q parallel to O $l$ meeting the ordinate B T in Q.

FIG. 187.



Then B T represents the pressure $p$, corresponding to the volume O T or length of cylinder $l$.

Also

$$\frac{dp}{dl} = \frac{\mathrm{BQ}}{\mathrm{RQ}} = \tan \alpha \,;$$

therefore,

$$\mathrm{TB} - \mathrm{TQ} = \mathrm{BQ} = l\frac{dp}{dl},$$

and formula (1), page 438, becomes

$$q = \frac{1}{\gamma - 1}\left(\gamma p + \mathrm{BQ}\right)$$

Hence measure B Q to the same scale as the pressures, add to it $\gamma$ times B T, divide the sum by $\gamma - 1$, and the quotient is the ordinate $q$ of the heat reception curve for that position $l$ in the piston stroke.

If the tangent were drawn at a point on the expansion curve B C, tan $\alpha$, and consequently B Q would likewise be negative. This, in common with all graphic methods which involve drawing tangents to curves, does not give very reliable results.

# CHAPTER XV.

## COMBUSTION IN THE ENGINE CYLINDER.

### TEMPERATURE OF COMBUSTION.

WE had an explosive mixture, in the combustion engine cylinder, made up of 1 cubic foot coal gas to 5·76 cubic feet of air. Let us suppose that the combustion is complete and instantaneous, so that there is not time for either loss or gain of heat through the cylinder walls. We find as a result that 1 cubic foot of rich coal gas, when thoroughly burned and the products cooled to the same temperature as before ignition, gives out 378 units of heat, and the mixture reduces to 6·5 cubic feet.

What then ought to be the highest temperature at the moment of explosion?

By calculation, the specific heat at constant volume of the products is about 0·2, on the assumption that the specific heats of the gases are the same at all temperatures. We know that the number of units of heat given to a perfect gas equals its *weight* × *specific heat* × *rise in its temperature.*

Now one pound's weight of the products of combustion occupies 13·44 cubic feet, so that 6·5 cubic feet weigh $\frac{6{\cdot}5}{13{\cdot}44}$ or ·4837 lb.

Substituting these values in the formula

$$w \times s \times t = \text{H},$$

we have

$$\cdot 4837 \times \cdot 2 \times t = 378,$$

whence

$$t = \frac{378}{\cdot 4837 \times \cdot 2}, \text{ or about } 3900^\circ \text{ C.}$$

This gives us a roughly approximate idea of the maximum rise of temperature to be expected.

The true average temperature of a mixture of masses of gas having thermal capacities $m_1$, $m_2$, $m_3$, &c., at temperatures $T_1$, $T_2$, $T_3$, &c., is

$$\theta = \frac{m_1 T_1 + m_2 T_2 + \&c.}{m_1 + m_2 + \&c.}.$$

If the gases are all at the same pressure $p$ and occupy volumes $v_1$, $v_2$, &c., whose sum $= v$. Let $m_1 + m_2 + m_3 + \&c. = 1$; and if $v_0$, $p_0$, and $T_0$ were the volume, pressure, and absolute temperature of the whole mass at a previous time, then

$$\frac{v_1 p}{T_1} = m_1 \frac{v_0 p_0}{T_0}; \quad \therefore m_1 T_1 = T_0 \cdot \frac{v_1 p}{v_0 p_0}.$$

Similarly,

$$m_2 T_2 = T_0 \cdot \frac{v_2 p}{v_0 p_0};$$

and so on for the others;

$$\therefore \theta = \frac{T_0 p}{v_0 p_0} \cdot \frac{v_1 + v_2 + \&c.}{m_1 + m_2 + \&c.} = \frac{T_0 p}{v_0 p_0} v; \text{ and } \frac{pv}{\theta} = \frac{p_0 v_0}{T_0}.$$

This gives the average temperature arrived at on the assumption that it is uniform throughout the whole mass. The calculation is hopelessly complicated by the fact that in the actual cylinder the gas in contact with the cold walls must form a cool envelope compared with the hot portion in the very centre of the cylinder, owing to the inferior conductivity of the gas, although rapid convection and expansion must take place.

We have seen in the previous chapter that the temperature actually obtained in the cylinder, as determined from the maximum pressure shown on the indicator diagram, was only 1413° C.; whereas the rough estimate, by calculation from the quantity of heat generated in complete combustion, assuming the specific heat constant, comes to about 3900° C.

What is the cause of this difference? Why is it that the explosion of a mixture of rich coal gas and air, which ought to produce a temperature of 3900° C., only gives a pressure in the cylinder corresponding to 1413° C.? It is evident that the whole heat of combination is not evolved at once or accounted for. The **latent heat of all the steam formed,** as well as that given out in cooling to 18° C., should have been deducted, as it is included in the total heat evolved by the combustion of unit weight of hydrogen. Thus, in the case of hydrogen alone, the heat of combustion $34{,}180 - (536 + 82)$ leaves 33,562 heat units available for increasing the temperature of the steam and other products. At the very high temperatures produced by combustion a large amount of heat is rendered latent in the gases (see page 356). But these causes are insufficient to account for so great a falling-off in the pressure.

Doubtless the answer is partially found in the fact that during the first violent reaction before the **combination** is complete, it is **retarded somehow,** and afterwards slow combustion is kept up during the whole expansion stroke. On a careful examination of the indicator curve this retardation is clearly shown, and we have calculated, Fig. 186, the rates at which the heat is being evolved, over and above that lost to the water-jacket, for the different parts of the expansion curve. It is obvious from this heat reception curve that at the very beginning of the stroke there is a tremendous evolution of heat; this is suddenly checked, falls off during the ignition period, and much more rapidly towards the end of the combustion period, but never quite ceases. In fact, there is a considerable evolution of heat taking place at the end of the stroke, and we find that combustion takes place and heat is evolved from the moment at which the gas is ignited until it escapes from the engine cylinder.

This partly accounts for the lower initial temperature; but what is the cause of this continued combustion? What laws control the explosion of a gaseous mixture, such as coal gas and air, in a closed vessel like the cylinder of an internal combustion engine?

The conditions of combustion are so complex in the actual engine cylinder that the best way to approach the study of the subject is to observe the results of combustion experiments under simplified conditions.

In 1861, HIRN made experiments* to determine the pressures produced by the explosion of mixtures of hydrogen and air, also of coal gas and air. The explosion vessels used were two copper cylinders of the same axial length as diameter, and, like the Lenoir gas-engine cylinders, the capacity of one being 36 litres and the other 3 litres. The pressure was registered by a Bourdon spring manometer. A mixture in the proportion of 1 volume hydrogen with 9 volumes of air, which by calculation should give a maximum pressure of 5·8 atmospheres, was found by experiment to produce an explosion pressure of only 3·25 atmospheres. With mixtures of coal gas and air, similar results were observed. A mixture containing 1 volume lighting gas to 9 volumes of air gave, by experiment, only five atmospheres, much below the calculated pressure. He points out that the pressure produced by hydrogen is low, as it should be, compared with that given by an equal volume of coal gas, which is 4 or 5 times as heavy as hydrogen.

Hirn explains that the difference between the calculated pressures and those observed by experiment is due to the **cooling effect of cold enclosing walls,** by which the heat is conducted away rapidly as it is evolved by explosion, so that it is impossible to reach the highest temperature, accordingly the pressure falls short of what it would be if no heat were lost to the walls during the explosion.

In the introduction to Hirn's work, Grasshof says, "In the Lenoir engine the cylinder in all cases rapidly conducts away the heat, and a moderately high piston-speed is necessary to secure economy. There will be, for every proportion of gaseous mixture, a definite piston-speed and temperature of cylinder which will give the best result, and which can only be proved experimentally."

BUNSEN, in 1866, made some experiments † in which he exploded hydrogen and oxygen in a small vessel closed by a plate pressed down on the top of the vessel by a loaded piston. The mixture was fired by passing a spark through the whole length of the vessel to make sure of an instantaneous spread of the flame throughout the mass. Bunsen estimated the explosion pressure by the weight which was just lifted by the heated gases. With the cover-plate too heavily loaded he got only a silent flash, then he reduced the weight until, upon passing the spark, he found the plate lifted. With hydrogen and oxygen he found that, with a pressure of 9·5 atmospheres, the weight was lifted, but with 10 atmospheres the explosion was kept back. Assuming that the specific heats of steam and the combining gases remained constant, and that the heat evolved raised the gases instantaneously to the highest temperature attained, Bunsen argued that only one-third of the total quantity of hydrogen and oxygen could have entered into combination at once, the other two-thirds not being able to unite at that temperature, and as the whole mass cools down, another one-third unites, and so on until all the free gases are combined. With hydrogen burning in oxygen, Bunsen's experiments show a maximum temperature of about 3800° C., and in air 2000° C.

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* "Zur Theorie der Lenoirschen Gasmaschinen," *Polytechnisches Central-Blatt*, Leipsic, 1861.

† "On the Temperature of the Flames of Carbonic Oxide and Hydrogen," by R. Bunsen, *Phil. Mag.*, 1867, vol. xxxiv. p. 489.

## Dissociation.

Sainte-Claire Deville found that the chemical decomposition of steam into hydrogen and oxygen by the agency of heat commences from about 1000° C. to 1200° C. under atmospheric pressure. This separation or intramolecular transformation is called dissociation. If the temperature be raised, further dissociation takes place until a limit is reached when the steam is completely decomposed. For any temperature within these limits, with the same conditions of pressure, there is a definite percentage of the whole dissociated. If the temperature be lowered, recombination of the free gases takes place until equilibrium is established.

With carbonic acid, dissociation also commences between

1000° C. and 1200° C., a larger percentage is dissociated with absorption of heat at 1500° C., and still more at higher temperatures. If within the limits of dissociation the temperature of the free gases be lowered, recombination occurs and heat is disengaged. The rapidity of lowering the temperature, due to the loss of heat through the walls, also affects the recombination.

On the other hand, the more recent experiments* of MALLARD and LE CHATELIER go to prove that the dissociation of $CO_2$ only becomes perceptible about 1800° C., and is still very feeble at 2000° C.—even less than 5 per cent. Steam does not appear to dissociate until temperatures beyond 2500° C. are reached, and at 3300° C. the effect is negligible. Hence it would appear that dissociation does not come much into play in the combustion of dilute mixtures of gas and air in the combustion engine cylinder.

There is very little known about *dissociation*, and somewhat vague theories have been advanced to explain the phenomenon. However, experiment has established the fact that when an explosive gaseous mixture is enclosed in a non-conducting vessel so that very little heat is abstracted, *only a limited temperature or pressure is produced by combustion*, which, therefore, cannot be complete and instantaneous, but must be gradual and progressive.

It would further appear from Bunsen's experiments on the rate of flame propagation in an explosive mixture like that in the combustion engine cylinder, that the hydrogen and hydrocarbons combine first with the oxygen forming steam ($H_2O$), the carbonic oxide ($CO$) is very much slower in combining to form carbonic acid ($CO_2$); afterwards, as the temperature rises, the reaction is retarded, and when some steam and $CO_2$ are formed, these become split up in the presence of the carbon which tends to decompose the steam, taking up its oxygen and leaving free hydrogen, which finally reacts with the carbonic acid.

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* *Recherches sur la combustion des mélanges explosifs*, pp. 185 and 273, and *Comptes Rendus*, t. xciii. p. 962, 1881.

## RATE OF FLAME-PROPAGATION.

BUNSEN measured the velocity of propagation of inflammation in explosive gaseous mixtures. He ignited the explosive mixture as it issued from a narrow orifice in the containing vessel in which the pressure is lowered, until the flame passes back through the orifice and inflames the whole mass of the mixture. This back ignition takes place when the velocity with which inflammation is propagated from the upper burning layers of gas down through the whole mass is slightly greater than the rate of flow of the gas from the orifice. By this method Bunsen found the velocity of inflammation, 34 metres per second in the mixture 2 volumes of H and 1 volume of O, and about 1 metre per second in the mixture 1 volume CO and 1 volume O.

MALLARD and LE CHATELIER made determinations on the velocity of flame propagation in a long tube, closed at one end and open to the atmosphere at the other. Two conditions are necessary for the spread of combustion in a gaseous mixture: (1) the gas must be inflammable, that is, capable of being ignited by increase in temperature at any point; and (2) the heat evolved by combustion must be sufficient to ignite the uninflamed particles. The rate at which the flame spreads thoroughout the mixture from particle to particle when ignited at the open end is the true velocity of propagation. This velocity varies with (1) the initial temperature of the flame, (2) the mechanical agitation or disturbance of the explosive mixture, (3) the size of the igniting flame and the projection of the ignited portion into the mixture, as well as (4) with the diameter of the tubes used.

The experimental results,* within 10 per cent. error given, show that the velocity of ignition is 20 metres per second in the explosive mixture 2 volumes H and 1 volume of O;

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* *Annales des Mines*, 1871, 3$^e$ livraison.

becomes 10 metres per second for 1 volume H and 1 volume O. The velocity is 1·01 metre per second for a mixture 1 volume of coal gas to 5 volumes air, 0·285 metre per second in a mixture of 1 volume coal gas to 6 volumes air, and 0·25 metre per second in poor mixtures.

When both ends of the tube are closed, the velocity of ignition is much greater, because the expansion due to the inflammation projects the flame into the mixture, and ignition is thus accelerated. In this way the velocity became 1000 metres per second for the explosive mixture 2 volumes H and 1 volume O, whilst even dilute mixtures gave a sharp explosion.

BERTHELOT and VIEILLE have been led by experiment * to look upon detonation or explosion as rapid combustion propagated through a gaseous mixture by an undulatory motion or *explosive wave*, that is, a certain regular surface along which combination occurs. The flame is transmitted through the entire mass from layer to layer, with a velocity depending on the nature of the gaseous mixture. Combustion accompanies the explosive wave in such a way that the rate of propagation is the same for the ignition as for the maximum pressure immediately developed at the contact of the inflamed layer with the preceding one. It seems that in an explosion a considerable number of gaseous molecules, first ignited, are projected forward into the unburnt gaseous mixture with a velocity corresponding to the maximum temperature produced by the chemical combination; the *shock* causes ignition in the adjacent particles, and is transmitted through the mixture with a rapidity nearly equal to the mean velocity of the gaseous molecules. With a velocity less than this, or at temperatures below 1700° C. or 2000° C., propagation by the explosive wave ceases, and we have combustion by gradual spread of the flame from particle to particle. Hence the explosive wave cannot be easily produced in the ordinary combustion engine cylinder. Besides, the limits of combustion and detonation are quite distinct.

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* *Comptes Rendus de l'Académie des Sciences*, 1882, 16th and 23rd January, 27th March, 24th and 31st July; and *Sur la force des Matières Explosives*, vol. i. ch. vii.; also important paper read before l'Académie des Sciences, 18th March, 1884; and see *Annales de Physique et de Chimie*, 6th series, vol. iv. 1885, pp. 13–90.

A velocity of 2810 metres per second was found for the explosive mixture of hydrogen and oxygen in tubes 40 metres long and 5 millimetres diameter. This velocity is practically independent of pressure between ½ and 1½ atmosphere, and is the same for the tubes used between 5 and 15 millimetres. It is retarded by inert gases, which, when present in excess, prevent ignition, whilst increase of temperature or pressure favours propagation.

Marsh gas becomes inflammable with 6 times its volume of air, the explosion reaches a maximum with 8 or 9 times the volume of air, and ceases with 16 volumes.

A mixture of 1 volume coal gas to 14 volumes air was ignited without compression.

Berthelot and Vieille observed in other experiments that the maximum pressure produced by explosions, at constant volume, is always less than the pressure which would be developed if the system retained all the heat due to the reaction ; because there is always loss of heat due to radiation and contact with the walls of explosion vessel. This difference becomes greater, the smaller the ratio of the mass of gas to the volume or surface of the containing vessel, and the slower the combustion.

In 1884 these experiments were made with three explosion vessels of capacities 300 cubic centimetres, 1500 cubic centimetres, and 4 litres. The vessels of 300 and 4000 cubic centimetres capacity were cylindrical in shape, each fitted with a registering piston, and ignition was by the electric spark in a tube. The distance from the ignition point to the piston was 248 millimetres in the large vessel, and 128 millimetres in the small one.

*The time of explosion is the interval that elapses between ignition and the production of maximum pressure.*

Some of the experimental results are here tabulated :—

| No. | Mixture. | Time of Explosion. | |
|---|---|---|---|
| | | ¼-litre vessel. | 4-litre vessel. |
| | | second. | second. |
| 1 | $H_2 + O_2$ .. .. .. .. .. .. | 0·0010 | 0·0021 |
| 2 | $H_2 + O_2 + H_2$ .. .. .. .. | 0·0017 | 0·0042 |
| 3 | $H_2 + O_2 + 2O_2$ .. .. .. .. | .. | 0·0082 |
| 4 | $H_2 + O_2 + N_2$ .. .. .. .. | 0·0027 | 0·0069 |
| 5 | $H_2 + O_2 + 4N_2$ .. .. .. .. | .. | 0·0364 |
| 6 | $C_2H_4 + 4O_2$ .. .. .. .. .. .. | 0·0012 | .. |
| 7 | $C_4H_4 + 6O_2$ .. .. .. .. .. .. | 0·0029 | .. |
| 8 | $C_4H_4 + H_2 + 7O_2$ .. .. .. .. | 0·0014 | .. |
| 9 | $C_4N_2 + 4O_2$ .. .. .. .. .. .. | 0·0016 | .. |
| 10 | $C_4N_2 + 4O_2 + N_2$ .. .. .. .. | 0·0061 | .. |
| 11 | $C_4N_2 + 2O_2 + 2N_2$ .. .. .. .. | 0·0104 | .. |
| 12 | $C_4N_2 + 2O_2 + 4N_2$ .. .. .. .. | 0·0298 | .. |
| 13 | $2CO + O_2$ .. .. .. .. .. .. | 0·0129 | 0·0155 |
| 14 | $4CO + 2O_2 + N_2$ .. .. .. .. | 0·0178 | .. |
| 15 | $2CO + O_2 + N_2$ .. .. .. .. | 0·0265 | .. |
| 16 | $2CO + O_2 + CO_2$ .. .. .. .. | 0·0272 | .. |
| 17 | $2CO + O_2 + 2CO_2$ .. .. .. .. | 0·0358 | .. |
| 18 | $2CO + 2O_2 + H_2$ .. .. .. .. | 0·0039 | .. |

It is evident, first of all, from these figures, that the time taken to ignite the same mixture is longer the larger the explosion vessel and the greater the distance between the point of ignition and the piston. Mechanical disturbance of the mixture near the point of inflammation is also found to favour the spread of the flame. The combustion is slower in proportion to the excess of combustible gas present which does not enter into combination. In mixtures of hydrogen and oxygen the retarding effect of the excess oxygen is about double that of an equal volume of hydrogen.

The presence of nitrogen retards the combustion of hydrogen more than that of carbonic oxide. This shows that the retardation is not due solely to the lowering of the temperature, which is the same in both cases, but also to the greater inequality between the velocity of the gaseous molecules. At the same time the inert gas lowers the temperature of combustion, and thereby diminishes the velocity of the molecules, and reduces the number of effectual collisions between particles susceptible of reciprocal action. Again, the presence of an excess of the burnt products still more hinders combustion: carbonic acid retards the combustion of carbonic oxide more than nitrogen does. On the other hand, increase of pressure and temperature aid effectual collisions and combination. The rate of combustion is slower for carbonic oxide than for hydrogen; whilst for cyanogen and hydrocarbons rich in hydrogen, the time is about the same as for hydrogen alone, which indicates that the hydrogen burns before the carbon, even in the case of complete combustion. Moreover, in the case of mixtures of hydrogen and carbonic oxide with oxygen, the rate of combustion is not the mean of the two rates, but the two gases appear to burn separately, each with its own rapidity of propagation. Hence the observed maximum pressure does not correspond to a uniform combination of the mixture. Thus, carbonic oxide and hydrogen, burned separately with oxygen in the 4-litre vessel, gave sensibly the same pressure, namely, 10·1 atmospheres and 9·9 atmospheres respectively. But for a mixture of equal volumes of these gases burning together, instead of the mean pressure, experiment gives a lower figure—8·7 atmospheres. The same is true of ethylene mixed with hydrogen, and the time of explosion indicates that hydrogen burns first.

## Temperatures of Combustion.

In further experiments (1885) on explosive gaseous mixtures, Berthelot and Vieille determined the pressure produced and the quantity of heat generated by exploding mixtures in spherical vessels, and registering on a revolving cylinder the law of displacement of a piston of known section and mass. From these data the temperatures of combustion, the specific heats, and amount of dissociation are calculated.

Two sorts of mixtures are considered—reversible and non-reversible. In reversible mixtures the compounds formed by combustion can, by dissociation, be split up into the original components; such as CO and O forming $CO_2$, and steam $H_2O$ giving H and O. In non-reversible systems, on the other hand, dissociation does not produce the original gases; thus a mixture of cyanogen and oxygen, on complete combustion yields $CO_2$ and N, whilst dissociation tends to yield O and CO, or even free carbon, O and N. The difficulties attending direct measurements at high temperatures are overcome by experimenting on *isomeric* mixtures containing the same elements in different states of combination, but all yielding an identical mixture after combustion.

Given the pressure P developed by an explosion, the temperature must lie between two extreme limits.

1st. **Higher limit**:—When there is complete combination and contraction, with no dissociation, a limit T° C. *above* the real temperature of combustion is calculated by the formula,

$$T = 273\left(\frac{P}{P_0}\frac{1}{r} - 1\right),$$

where $P_0$ stands for the initial pressure at 0° C., and $r$ the ratio of the volume occupied by the products completely combined to that of the same gases entirely dissociated. If the initial temperature be above zero, say $t$° C., then $P\left(\frac{t + 273}{273}\right)$ is used instead of P in the formula.

2nd. **Lower limit**:—On the impossible assumption of complete dissociation, no contraction, and none of the gases really combined, consequently no heat evolved, another limit, $T_1$° C., *lower* than the real temperature of combustion, is found by the formula,

$$T_1 = 273\left(\frac{P}{P_0} - 1\right).$$

These limiting temperatures, T and $T_1$, are brought very close in dilute mixtures containing inert gases, like nitrogen, as in the case of combustion by means of air, because the possible contraction is small.

## Specific Heats at High Temperatures.

Conclusions are deduced directly from the observed results of numerous experiments with isomeric mixtures, under different conditions as regards density and heat generated by explosion, and independent of all hypotheses as to the laws of gases or their chemical constitution.

For temperatures up to 3000° or 4000° C. on the air-thermometer :—

1. When a given quantity of heat is supplied to a gaseous mixture, the variation in the pressure is proportional to the density of the mixture.

2. The specific heat of gases is sensibly independent of the density at very high temperatures as well as about zero.

3. The pressure increases with the quantity of heat given to the mixture.

4. The apparent specific heat increases with this quantity of heat.

The general results agree with those found by Mallard and Le Chatelier,* i. e., that the specific heat of gases increases with the rise of temperature, and that the simple elementary gases, as nitrogen, have sensibly the same specific heat at all temperatures. Between 0° and 200° C. the specific molecular heats, at constant volume, of these gases are about 4·8; this number is doubled in passing from 0° to 4500° C., becoming then 9·8. The variation takes place at all temperatures; it is inappreciable from 0° to 200°, but increases more rapidly at high temperatures.

The mean *specific heat of steam* at constant volume between 130° and 230° C., being 6·65, it is doubled at 2000° and trebled at 4000° C.

The *heat evolved in the formation of water continually diminishes as the temperature rises* (see page 356). This is partly due to the heat spent in the work of molecular separation without decomposition and partly to the heat absorbed in dissociation. It is roughly estimated that about 3000° C. dissociation would absorb at most 6600 calories, that is, one-seventh of the heat of combustion, whilst molecular separation would take up at least 8600 calories, or about one-fifth of the heat of combustion at this temperature. Evidently the effect produced by increase in specific heat and that due to dissociation are identical, as heat is absorbed by the gas in both cases.

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* *Comptes Rendus des Séances de l'Académie des Sciences*, 1880–81, tomes 91, 93. *Annales des Mines*, 1883.

The mean specific heat of carbonic acid at constant volume between 0° and $t$ is given by the formula

$$19{\cdot}1 + 0{\cdot}0015\ (t - 2000),$$

where $t$ is from 2000° to 4300° C.

The experimental results show that, as in the case of water, the heat of combustion of CO to form $CO_2$ diminishes as the temperature rises above 200° C. Thus it is calculated that about 4500° C. the heat of combustion would be 28,000 calories, and dissociation would absorb at most 18,000 calories, or two-thirds of the heat, whilst at least 22,000 calories would be used up in the work of molecular separation.

At 0° C. the heats of combustion in the formation of $H_2O$ and $CO_2$ are 58,700 calories and 68,000 calories respectively, whilst at 3000° C. they become 26,000 and 38,000.

It would thus appear that their ratio decreases as the temperature increases, and in experiments with these as the products of combustion in closed vessels at very high temperatures, the carbon tends to entirely decompose the steam.

MALLARD and LE CHATELIER were the first to *measure* the continuous increase in the specific heats with temperature. From results of experiments they deduced the following empirical formulæ, which enable us to calculate the specific heats C, at constant volume, for molecular volumes at high temperatures $t°$ C.:—

Nitrogen .. ($N_2 = 28$): $C = 4{\cdot}8 + {\cdot}0006\,t$.
Steam .. ($H_2O = 18$): $C = 5{\cdot}61 + {\cdot}00328\,t$.
Carbonic Acid ($CO_2 = 44$): $C = 6{\cdot}3 + {\cdot}006t - {\cdot}00000118\,t^2$.

Reduce these to unit weight of the substances, and we find the specific heats at constant volume :—

| NAME OF GAS. | | $C_v$ at 1500° C. | $C_v$ at 2000° C. | Ratio $\gamma = \frac{C_p}{C_v}$ at 2000° C. |
|---|---|---|---|---|
| Steam .. .. .. .. .. .. | $H_2O$ | ·59 | ·677 | 1·12 |
| Carbonic acid .. .. .. .. .. | $CO_2$ | ·29 | ·308 | 1·12 |
| Nitrogen .. .. .. .. .. .. .. | N | ·20 | ·215 | 1·33 |

### *Calculation of Temperature.*

If we suppose the combustion complete and instantaneous, we may calculate the unknown temperature $t°$ C. attained when the total heat H is evolved. From H we must deduct the quantity retained in the steam as latent heat of evaporation. Now since

$$t \Sigma w s = \text{H}, \quad \therefore t = \frac{\text{H}}{\Sigma w s},$$

the temperature $t°$ C. is found by dividing the heat generated H, by the sum of all the products obtained by multiplying the weights of the different constituent gases into their specific heats. (See above, pages 371–373.)

This is for combustion at constant volume, in which case we know by the law of Charles, $\frac{p}{p_0} = \frac{\text{T}}{\text{T}_0}$, the pressures are proportional to the absolute temperatures. If the combustion takes place at initial atmospheric pressure, $p_0 = 1$, and $\text{T}_0$ is atmospheric temperature added to 273 whilst $\text{T} = t° + 273$. Hence $p = p_0 \frac{\text{T}}{\text{T}_0}$ atmospheres, the pressure we should expect. When the mixture is compressed, making $p_0$ two or three atmospheres before ignition, then the pressure produced by combustion should be increased in the same proportion. In this calculation we have neglected the loss of heat to the cold enclosing walls, a very large factor, which doubtless plays an important part, and to a great extent controls internal combustion engine phenomena.

## EXPLOSION IN A CLOSED VESSEL AT CONSTANT VOLUME.

Mr. Dugald Clerk made some *experiments* [*] *on* **explosive mixtures kept at constant volume** *in a closed vessel.* The explosion-vessel was a strong cast iron cylinder, 7 inches internal diameter, and 8½ inches long, so that the constant volume was 317·5 cubic inches. It was completely closed by end covers, firmly bolted on.

A Richards' Indicator was mounted on the upper cover, the ordinary reciprocating drum being replaced by an enamelled one, revolving uniformly at known speed, whilst a soft black lead pencil recorded on it the movements of the indicator-piston, which showed the changes of pressure in the explosion vessel.

The different mixtures, introduced *at atmospheric temperature and pressure*, were fired by the electric spark, and the lines traced by the indicator pencil on the revolving drum show the variations in pressure at every instant during the combustion, until the fall becomes gradual and regular, due simply to the conduction of heat away by the cold walls of the vessel.

Taking three different mixtures of hydrogen and air, the curves shown in Fig. 188 were traced out. As defined above, the time of explosion is the interval of time that elapses between ignition and the production of maximum pressure.

EXPLOSION AT CONSTANT VOLUME.

| CURVES. | MIXTURES USED. | Temperature before Explosion. | Time of Explosion. | Maximum Pressure above Atmosphere. | | Maximum Temperature. | |
|---|---|---|---|---|---|---|---|
| | | | | Observed. | Calculated. | No Contraction. | Complete Contraction. |
| | | C. | | | | C. | C. |
| *a* | 1 volume H to 6 vols. air | 16° | ·15 sec. | 41 | 88·3 | 826° | 909° |
| *b* | 1 " " 4 " | " | ·026 " | 68 | 124 | 1358° | 1539° |
| *c* | 2 " " 5 " | " | ·01 " | 80 | 176 | 1615° | 1929° |

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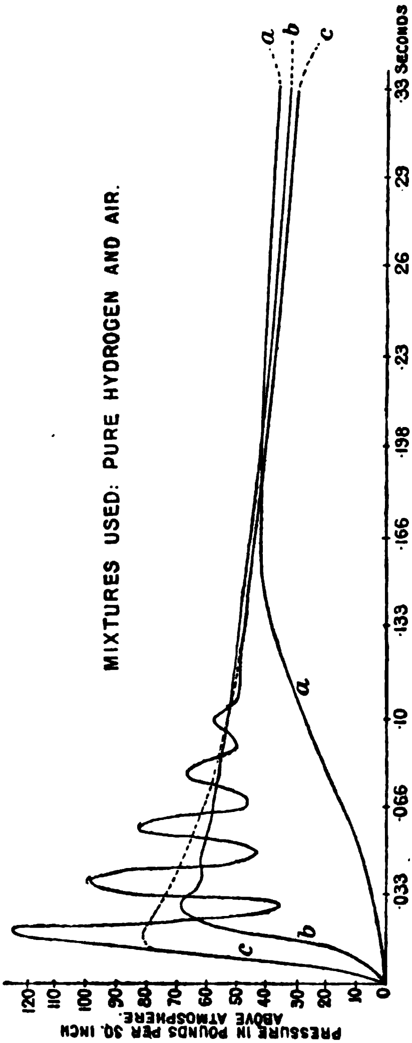
[*] *Minutes of Proceedings Inst. C.E.*, vol. lxxxv. 1886, p. 1.

Fig. 188.

MIXTURES USED: PURE HYDROGEN AND AIR.



The maximum pressure is calculated on the assumption that all the heat is evolved when maximum pressure is attained, and that the average specific heat of the mixed gas $H_2O$, O, &c., remains, 0·2, unaltered at high temperatures. It is evident that the combination cannot be complete when the highest pressure is reached. With 1 volume hydrogen to 6 volumes of air, there is a large excess of air, and the curve *a* shows a slow rise of pressure and temperature; the mixture 1 volume of H to 4 volumes of air, has a more rapid explosion, as shown by curve *b*; whereas the rich mixture, curve *c*, gives a very quick rise, and an explosion so rapid that a rap was heard as of a sharp blow with a small hammer on the indicator piston, the previous ignitions being noiseless.

The maximum temperatures in the table are calculated by Berthelot's method of limits (page 452).

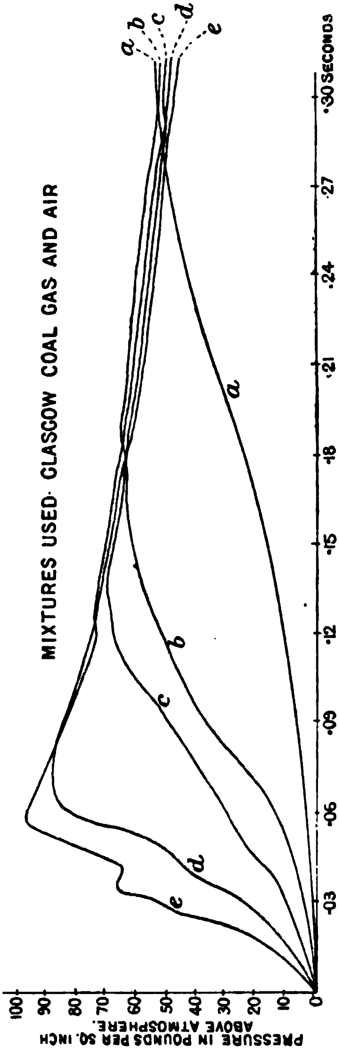
The indicator-diagrams Fig. 189 show the results obtained when different mixtures of Glasgow coal gas and air are burned, the temperature before ignition being 18° C., and the pressure atmospheric.

EXPLOSION AT CONSTANT VOLUME.

| CURVE. | MIXTURES USED. | Time of Explosion (seconds). | Maximum Pressure above Atmosphere in lb. per sq. in. | Temperature of Explosion calculated from observed Pressure. |
|---|---|---|---|---|
| | | | | ° C. |
| *a* | 1 volume coal gas to 13 vols. air .. | 0·28 | 52 | 1047 |
| *b* | 1 " " " 11 " .. | 0·18 | 63 | 1265 |
| *c* | 1 " " " 9 " .. | 0·13 | 69 | 1384 |
| *d* | 1 " " " 7 " .. | 0·07 | 89 | 1780 |
| *e* | 1 " " " 5 " .. | 0·05 | 96 | 1918 |

The maximum temperatures are calculated supposing no change in volume by combustion, and that the mixture behaved like a perfect gas. The highest pressure is only 96 lb. per square inch above atmospheric, and the pressure falls gradually off with the rate of combustion as the mixture is made more

FIG. 189.


MIXTURES USED· GLASGOW COAL GAS AND AIR
PRESSURE IN POUNDS PER SQ. INCH ABOVE ATMOSPHERE.
0
10
20
30
40
50
60
70
80
90
100
TIME
·03
·06
·09
·12
·15
·18
·21
·24
·27
·30 SECONDS
a
b
c
d
e
a
b
c
d
e

dilute, until with less than 1 volume of gas to 13 volumes of air, the mixture at 18° C. and atmospheric pressure cannot be ignited by the electric spark.

The results clearly prove that combustion is gradual, and under these conditions may be controlled by dilution of the mixture. In vessels of different volume and shape the times of explosion would be altered.

The peculiar hump in the rising curve *e*, Fig. 189, after ·03 second, is not due to any defect in the indicator, but represents a pause in the increase of temperature or rate of combustion. When the mixture has become inflamed throughout its entire mass before the reaction is complete, some of the hydrocarbons present may become decomposed, and the absorption of heat, as well as the check in combustion, may cause this sudden change in the rate of rise of the pressure.

Similar experiments with mixtures of Oldham coal gas and air in the closed vessel gave the curves Fig. 190.

EXPLOSION AT CONSTANT VOLUME.

| CURVES. | MIXTURES USED. | Temperature before Explosion. | Time of Explosion (seconds). | Maximum Pressure above Atmosphere. | | Temperature of Explosion. | |
|---|---|---|---|---|---|---|---|
| | | | | Observed. | Calculated. | From Observed Pressures. | If all heat Evolved. |
| | | C. | | | | C. | C. |
| *a* | 1 vol. gas to 14 vols. air | 18° | 0·45 | 40 | 89·5 | 806 | 1786 |
| *b* | 1 „ „ 13 „ | 16·2 | 0·31 | 51·5 | 96 | 1033 | 1912 |
| *c* | 1 „ „ 12 „ | 16 | 0·24 | 60 | 103 | 1202 | 2058 |
| *d* | 1 „ „ 11 „ | 16·1 | 0·17 | 61 | 112 | 1220 | 2228 |
| *e* | 1 „ „ 9 „ | 16·7 | 0·08 | 78 | 134 | 1557 | 2670 |
| *f* | 1 „ „ 7 „ | 16·7 | 0·06 | 87 | 168 | 1733 | 3334 |
| *g* | 1 „ „ 6 „ | 16 | 0·04 | 90 | 192 | 1792 | 3808 |
| *h* | 1 „ „ 5 „ | 16 | 0·055 | 91 | | 1812 | |
| *i* | 1 „ „ 4 „ | 19 | 0·16 | 80 | | 1595 | |

A mixture of 1 volume gas to 15 volumes air failed to ignite with the electric spark at atmospheric pressure in the

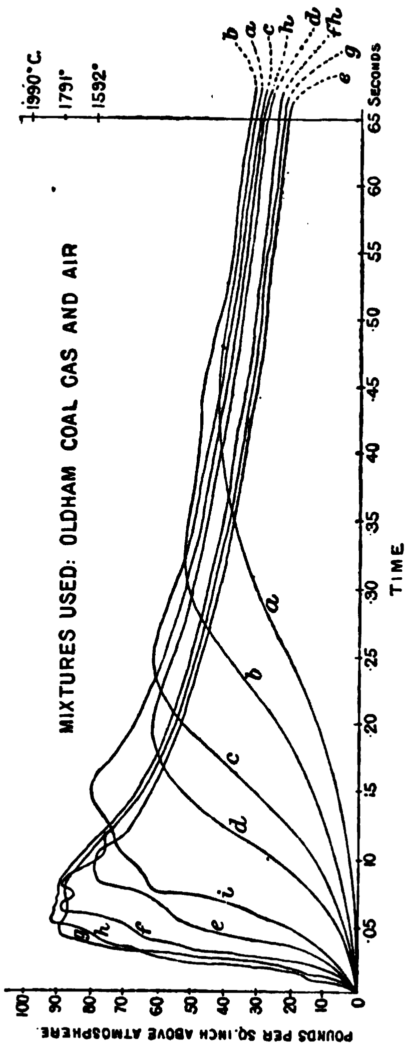

MIXTURES USED: OLDHAM COAL GAS AND AIR
1990°C.
1791°
1592°
b
a
c
h
d
f h
g
e
a
b
c
d
i
e
f
h
g
100
90
80
70
60
50
40
30
20
10
0
POUNDS PER SQ. INCH ABOVE ATMOSPHERE
0
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
·55
·60
·65 SECONDS
TIME

FIG. 190.

closed vessel; whilst the greatest pressure produced by the explosion of a mixture of this gas and air was 91 lb. per square inch above the atmosphere.

In experiments with a mixture of constant composition, only compressed to double the original pressure at 18° C. before ignition, the pressure produced by explosion was doubled; showing that *the explosion pressures for any mixture are proportional to the pressure before ignition.*

From these results of his experiments, Mr. Clerk deduces the relative values of the different mixtures to produce pressure in a non-compression gas engine, with cylinder similar to this explosion-vessel. The best mixture must not only evolve heat to produce the greatest pressure for a given volume of gas, but it must also best sustain the pressure by prolonged combustion, to overcome cooling and other effects, so as to give out the greatest power during the time taken by the piston to make the explosion or working part of its stroke, about 0·2 second in the modern gas engine.

Taking one cubic inch of coal gas, with different proportions of air, the mixtures that give the highest average pressure during 0·2 second are: Glasgow gas mixture, 1 volume of gas to 11 volumes gives 666 lb. pressure; with a mixture containing $\frac{1}{14}$th gas the pressure is 665 lb.; all the others give less, so that the mixture containing $\frac{1}{12}$th of gas, is the best for non-compression engines. With Oldham coal gas the best mixture is 1 volume gas to 12 volumes air, which gives 663 lb. average pressure, during 0·2 second, per cubic inch of gas used in this explosion vessel at constant volume, the heat being only conducted away by the walls of the vessel. The mixture containing $\frac{1}{14}$th of Oldham gas gives 640 lb. pressure, and the mixture with $\frac{1}{12}$th part gas gives only 630 lb. pressure during 0·2 second.

These figures will not hold true for cylinders or explosion vessels of different volumes and cooling surfaces.

However, these experiments show that weak mixtures, by gradual combustion, give a well-sustained pressure per unit volume of coal gas used; and to obtain the rapidity of combustion to suit the speeds of modern engines, it becomes necessary to compress these mixtures before ignition.

Mechanical agitation aids ignition and combustion. The expansion due to the piston movement alters the surface of exposure, and fresh complications are introduced by other such practical conditions.

## EXPLOSION FOLLOWED BY EXPANSION.

Professor AIMÉ WITZ, of Lille, has studied the combustion* of explosive mixtures, under the conditions that obtain in the modern internal combustion engine cylinder, and draws special attention to the **cooling action of the cylinder walls** *when the mixture is allowed to expand doing external work after ignition.*

Dr. Witz used a cast iron cylinder, internal diameter 200·1 millimeters (8 inches), and 400 m.m. high. A piston, with bronze packing is moved upwards through a travel of 323 m.m. in this cylinder, by the burning and expanding mixtures. The piston is 77 m.m. thick, and weighs 14·5 kilograms (about 32 lb.). The resistance to motion by the friction of the bronze rings offers a retarding force of 17 kilograms. Therefore the force required to lift the piston is 31·5 kilograms.

The upward motion of the piston can be accelerated or retarded at will, by means of either a counterpoise weight or a brake. In one case a cord attached to the piston-rod, and wound round a pulley, transmits the pull of a mass 75 kilograms falling down a groove; in the other case, a pressure ring acts as a brake on the piston-rod, and can stop the motion when necessary. By this twofold arrangement the speed of piston, and consequently the rate of expansion, can be varied by the experimenter from 0·25 to 10 metres per second. A water-jacket round the cylinder keeps the walls at any desired temperature.

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* *Annales de Chimie et de Physique*, 5th series, vol. xv. p. 433 (1878); vol. xviii. p. 208 (1879); vol. xxiii. p. 131 (1881); vol. xxx. 5th series, 1883; also *Etudes sur les Moteurs à gas tonnant.*

The explosive mixture, admitted under the piston, is ignited by an electric spark from an induction coil, flashing at a small cavity in the cylinder-wall. The explosion produced drives the piston upwards, against the atmospheric pressure, its own weight, and friction.

The pressure under the piston is recorded by a Richards' indicator mounted on the cylinder, and the drum motion is regulated by a cord attached to the piston-rod; so that the diagrams traced out have the ordinates proportional to the pressure, and abscissæ proportional to the volumes occupied by the gas. The indicator springs used in these trials moved 1 millimeter for pressures of 35, 70, and 139 grammes per square centimetre.

A tuning-fork, kept in vibration, carries a light style on one limb, and traces a wavy line, and this measures the time with extreme accuracy. The tuning-fork made 128 simple vibrations per second, so that it was easy to observe the time to less than the $\frac{1}{200}$th of a second.

The indicator-diagrams revealed the characteristics of the explosions, and their areas represented the work done by a known quantity of gas under given conditions.

By regulating the expansion, the temperatures and pressures produced by the explosion could be reduced. Lowering the temperatures gets rid of the effects of dissociation, which do not occur below 1500° C.; also, by reducing the pressures, the vibrations of the indicator springs are avoided.

The coal gas was found to vary from day to day, in quality, composition, and heating power. The latter was taken as 5250 calories per cubic metre of gas.

First of all, the *effect produced on an explosion by the rate of expansion* was experimentally investigated. The piston speed is represented by $\frac{d\iota}{dt}$, the ratio of piston travel to the short interval of time occupied.

| MIXTURE. | Time of Explosion $t$. | Travel of Piston, $l$. | Speed of Piston, $\frac{dl}{dt}$. | Work calculated from Diagram $w$. | Theoretical Work, W. | Efficiency, $\eta = \frac{w}{W}$. |
|---|---|---|---|---|---|---|
| By Volume. | seconds | millimetres | metres per second | kilogm.-metres | kilogm.-metres | per cent. |
| 1 coal gas to 9·40 air (3·096 litres) | ·53 | 188 | ·36 | 9·8 | 680 | 1·4 |
| ,, ,, | ·42 | 203 | ·49 | 10·5 | ,, | 1·5 |
| ,, ,, | ·40 | 203 | ·50 | 11·8 | ,, | 1·7 |
| ,, ,, | ·35 | 211 | ·60 | 12·3 | ,, | 1·8 |
| ,, ,, | ·25 | 229 | ·92 | 14·6 | ,, | 2·1 |
| ,, ,, | ·16 | 229 | 1·42 | 17·4 | ,, | 2·6 |
| 1 coal gas to 6·33 air (2·081 litres) | ·15 | 259 | 1·7 | 17·6 | 663 | 2·6 |
| ,, ,, | ·09 | 259 | 2·9 | 40·1 | ,, | 6·0 |
| ,, ,, | ·06 | 259 | 4·3 | 50·5 | ,, | 7·5 |
| ,, ,, | ·06 | 280 | 4·8 | 57·0 | ,, | 8·6 |

These results prove that *the useful effect increases with the velocity of piston*, that is, *with the rate of expansion of the burning gases.* The same holds for explosive mixtures of carbonic oxide and air of different richness. It was also found that with excessive dilution, combustion always remained incomplete.*

The time necessary for the explosion to attain its maximum pressure depends not merely on the composition of the mixture, but also upon the rate of expansion. Besides, with combustion at constant volume the maximum pressure is attained at the end of 0·045 second for the rich mixture, and 0·21 second for the weak mixture of coal gas and air.

In fact, if a mixture of gas and air be ignited behind a movable piston, experiment shows that the speed of inflammation, or the rate of flame propagation, increases with the piston-speed, with the initial pressure and temperature, and with mechanical agitation of the mixture. Previous compression renders the combustion more active.

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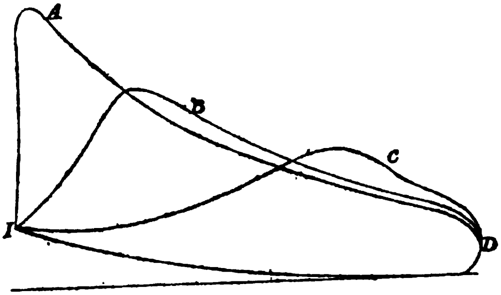
* *Comptes Rendus de l'Académie des Sciences*, vol. xcix. 20th July, 1884; vol. c. 10th Feb. and 27th April, 1885.

In the explosion gas engine with normal load, the speed of propagation of the flame is always greater than the piston speed. An Otto engine running at 150 revolutions per minute has a maximum piston speed of 2·71, or a mean speed of 1·78 metres per second.

The indicator diagrams, Fig. 191, taken from a good Otto engine with the same richness of gaseous mixture in each case, show the effect of the cold cylinder walls after several explosions were missed. The rate of combustion is slackened accordingly from the steep curve I A D to I C D, where the rate of inflammation lags behind the piston speed, the explosive pressure being reduced at the same time.

FIG. 191.



Dr. Witz gives the following resumé of his results:—

| MIXTURE. | Rate of Expansion $\frac{dl}{dt}$. | Time of Explosion $t$. | Maximum Pressure. |
|---|---|---|---|
| | metres per second. | seconds. | kilogrammes. |
| 1 vol. gas + 6·33 vols. air .. | 4·30 | ·045 | 7·39 |
| ,, ,, | 1·70 | ·141 | 6·70 |
| 1 vol. gas + 9·4 vols. air .. | 0·64 | ·219 | 5·24 |
| ,, ,, | 0·25 | ·468 | 4·53 |

The obvious conclusion from these figures is, that the combustion takes place faster, and consequently the pressure produced is higher, as the rate of expansion increases; and the previous results show that the area of the diagram, the work done, and efficiency, vary accordingly.

To utilise the greatest possible part of the available heat generated during the combustion of the charge in the engine cylinder, it is clearly necessary to make the expansion occupy as short a time as possible, and to reduce as far as possible the ratio of the cooling surface of cylinder-wall to the volume of the gas, that is, to make the ratio

$$\frac{\text{surface}}{\text{volume}} \text{ a minimum.}$$

Vieille also observed that the maximum explosive pressure depends on this ratio.*

Now the volumes of similar cylinders increase as the cube of the diameter, whilst the surface of their cold walls varies as the square of the diameter, so that for large cylinders the ratio of surface to volume is less than for small ones. This points to less waste as engines increase in power.

Hence also the advantage of realising the maximum value for $\frac{Q}{V}$, that is, the ratio of the quantity of available heat to the volume occupied by the explosive mixture which generates it; in other words, there is not only a theoretical advantage, but also a real practical gain, in compressing the gases before combustion.

This proves that the great success of the Otto and Langen atmospheric engine was undoubtedly due to its high piston speed.

Meidinger also points to the high piston-speed as the principal cause of the great economy of this motor over the Lenoir.

Again, notwithstanding the fact that the efficiency of any heat engine depends upon the range between its highest and lowest working temperatures, it is found economical to raise the temperature of the cylinder walls, within certain limits, to reduce the loss by cooling.

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* *Comptes Rendus*, t. xcv. p. 116, 1882.

During trials made in Rouen with a Simplex gas engine, having cylinder diameter 7·87 inches, and length of stroke 15·74 inches, the temperature of the cooling water being 62° C., the engine made 154·3 revolutions per minute, giving 6·7 horse-power on the brake, and consuming gas at the rate of 21·96 cubic feet per brake horse-power per hour. When the temperature of the cooling water was raised to 74° C., the speed increased to 161·2 revolutions per minute, giving 8·67 horse-power on the brake, and the gas consumption was only 20·65 cubic feet per brake horse-power per hour. This shows a saving of 7 per cent.

An Otto gas engine, having diameter of cylinder 6·75 inches, length of stroke 13 inches, and the volume of the compression space 0·61 of that swept by the piston, as tested by Dr. Slaby, required 9·5 per cent. less gas per brake horse-power by allowing the temperature of the cooling water round the cylinder to rise from 16° to 60° C.; Dr. Slaby attributes this chiefly to diminished friction.

Such experiments clearly show that in practical work, to obtain greatest economy per effective brake horse-power, it is necessary (1) to transform the heat into work with the very greatest rapidity mechanically allowable; (2) to have high initial compression; and (3) to reduce the duration of the contact between the hot gases and the cylinder walls to the smallest possible amount, by a high rate of expansion, while the cylinder walls are not too much cooled.

Dr. Witz sums up his conclusions as follows:—

"The influence of the cylinder walls is the chief regulator of explosive phenomena. It suffices either to retard or accelerate combustion, or to produce a slow and gradual combustion; there is no need to have recourse to the theories of dissociation to explain this prolonged reaction of the combining gases. As a matter of fact, slow combustion is obtained in the cylinder at temperatures so low as 1400° C., at which dissociation is impossible. Dilution renders this effect more apparent, because the mass of inert gas in which the active explosive gas is mixed, acts partly like the walls, that is to say, by cooling; but the prolonged combustion—the German 'nachbrennen,' or after-burning—may be produced independently of dilution."

Combustion ought not to be designedly slackened, or retarded. This is an imperfection which ought not to be striven for, Otto has therefore been wrong in doing so. Unfortunately, such retardation cannot be completely avoided, because the action of the walls can only be reduced, not totally suppressed. The success of Otto is due to *compression*, and not to the extreme dilution of the explosive mixture with the products of combustion of the previous charge. In fact, the point is, to reduce, as far as possible, not only the extent of cooling surface of the cold cylinder walls in contact with a given mass of gas by compression, but also to make the time of such contact very brief by high speed of piston.

## PRACTICAL RESULTS.

From a practical point of view, it is well that the whole heat of combustion is not evolved at once, because this would produce inconveniently high pressures, and the sudden shocks cause great mechanical stresses, which only enormous strength of metal could withstand. However, there is no danger in this regard, seeing the pressures produced by the explosion of mixtures of gas and air are under complete control.

The foregoing experiments abundantly prove that combustion takes place gradually in the gas engine cylinder, and the rate of increase of pressure or rapidity of burning is controlled by dilution and compression of the mixture, as well as by the rate of expansion or piston-speed. The rate of combustion also depends on the size and shape of the explosion vessel, and is increased by mechanical agitation or disturbance of the mixture, and still more by the mode of firing. A small intermittent spark gives the most uncertain ignition, whereas a continuous electric spark passed through an explosive mixture, and a large flame shooting a mass of lighted gas into a weak mixture, will produce rapid ignition. (See Chapter VII.)

Moreover, it is a fact, acknowledged by practical engineers, that *when the highest pressure is produced in the cylinder, only about one-half of the total heat of combustion of the charge is evolved*, the rest of the heat being developed during the expansion part of the stroke.

It is also very well known that a large amount of heat is carried away by the water which continually circulates round the cylinder. This heat is completely wasted, and only serves to keep the cylinder cool enough for proper lubrication.

From exhaustive trials of a 6 horse-power Otto engine, in 1883, Messrs. Brooks and Steward stated that 52 per cent. of the total heat was lost to the water-jacket. Professor Thurston estimates the heat thus rejected by the water-jacket from about 45 to 55 per cent. of the total heat of combustion.

In the Society of Arts motor trials, 1888–89, the heat carried off by this jacket-water round the cylinder was 43 per cent. in the Crossley engine, and this loss was reduced by rapid expansion to 27 per cent. of the whole heat of combustion in the Atkinson Cycle Engine working at full power.

| GAS MOTOR. | Gas used per brake H.P. per hour (cubic feet). | Rise of Temperature in Water Jacket. | Time of Expansion Stroke (seconds). | Heat Rejected in Water Jacket (percentage). |
|---|---|---|---|---|
| Atkinson "Cycle" | 22·61 | 50·0° F. | 0·11 | 27·0 |
| Crossley "Otto" .. | 24·10 | 128·0 | 0·20 | 43·2 |
| Griffin .. .. .. | 28·56 | 71·8 | 0·14 | 35·2 |

It is evident that the high piston velocity notably diminishes loss of heat energy by shortening the time of contact of the burning gas with the cold cylinder walls.

The Atkinson Cycle Engine expands the charge to double its volume before compression, so that in this engine the expansion to the original volume takes place in one-third and one-fourth of the times required in the Griffin and Crossley engines respectively. Hence these figures clearly prove that the effect of cooling surface may be reduced with economy by doing the work rapidly.

## Theories.

All those physicists who have experimented on the explosion of gaseous mixtures in closed vessels, agree that nearly half of the total heat of combustion is not accounted for by the maximum rise of pressure. But somewhat different *hypotheses* have been proposed to explain the causes limiting the temperatures produced.

LIMIT BY COOLING.—Hirn's theory is that, when an explosion takes place with sudden evolution of heat, the cooling effect of the walls increases, and a temperature is soon reached above which *heat is conducted away by the cold metal walls* more rapidly than it is evolved by the combustion, which is also thereby partly counteracted, and the greatest pressure attained falls far short of what it would be if no heat were lost.

Witz has very ably supported this view that *the cooling action of the walls regulates explosive phenomena.* His experiments prove that the useful effect, or brake horse-power is increased with rapid rate of expansion $\frac{dl}{dt}$; and at the same time high compression before combustion is also useful to make as great as possible the ratio, $\frac{Q}{V}$, of the available quantity of heat to the volume occupied by the mixture evolving it. He considers *the effect of the cold walls sufficient to explain slow combustion.* On the other hand, he admits that dilution does the same thing.

LIMIT BY INCOMPLETE COMBUSTION.—Professor Fleeming Jenkin clearly pointed out * that in the combustion of a complicated substance like coal gas, as in other chemical reactions, at first the reaction goes on rapidly though it is soon checked, and proceeds slowly as the dilution by the burnt products increases. At an early stage of the combustion some of the hydrocarbons may also be decomposed, with absorption of heat, which checks the rising temperature and pressure. According to this view, *the maximum pressure only indicates the time taken by the flame to spread throughout the entire mass, that is, maximum pressure shows complete inflammation or explosion, but not complete combustion.* Gradual combustion continues long after this, at rates depending on the nature and dilution of the mixture, as well as on the piston speed, according to Witz. Combustion proceeds more slowly as dilution increases, and as the piston speed decreases.

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* "Gas and Caloric Engines," in the series "Heat and its Mechanical Applications," *Proceedings Inst. C.E.*, 1883-4.

Mr. Dugald Clerk, considers that in "all gaseous explosions, as in other chemical actions, the first part of the reaction occurs rapidly, and proceeds with increasing difficulty as the combination approaches completion, and this action is one of the causes preventing the complete evolution of the total heat at the moment of explosion."

LIMIT BY DISSOCIATION.—Bunsen's theory is, that *dissociation or decomposition by heat at very high temperatures, accompanied by the absorption of heat, limits the temperature attained by any explosive mixture,* even in a vessel of non-conducting materials designed to reduce, as far possible, the loss by cooling.

We must imagine in the combustion engine cylinder that the gas in the very centre is at a high temperature and in a state of thermal equilibrium depending on the nature and pressure of the combining gases, such that when any definite temperature is reached a certain portion of the combined gas becomes dissociated and ready to enter into combination again when the temperature is lowered by the cooling action of the cylinder walls, or by the gases expanding and doing work on the piston. The result is, that instead of instantaneous and complete evolution of heat at the moment of ignition, a limiting temperature is soon reached, and gradual combustion follows as the temperature falls.

The action is very complicated, however, and the hypothesis that dissociation increases with the temperature fails to account for all the facts. For instance, in Clerk's experiments with hydrogen mixtures, the apparent evolution of heat was 55 per cent. when the maximum temperature of explosion was 900° C., and 54 per cent. at 1700° C. Moreover, mixtures of Oldham gas and air show the same apparent loss of heat at high as at low temperatures.

LIMIT BY INCREASE OF SPECIFIC HEAT.—Mallard and Le Chatelier conclude, from the results of their experiments, that the dissociation of carbonic acid only commences about 1800° C., and that of steam at temperatures above 2500° C., whilst at 3300° C. the dissociation of steam is negligibly small. On the other hand, they point out that the same limiting effect on the explosion temperature may be produced by the continued INCREASE OF THE SPECIFIC HEATS of the gases at very high temperatures.

The gross result is doubtless due more or less to all these four causes acting together, and not to any one of them alone, to limit the maximum temperature attainable by the explosion of any given mixture, and produce gradual combustion with continued evolution of heat throughout the explosion stroke.

# CHAPTER XVI

## TRANSFORMATION OF HEAT INTO WORK

### ACTION OF A PERFECT HEAT ENGINE.

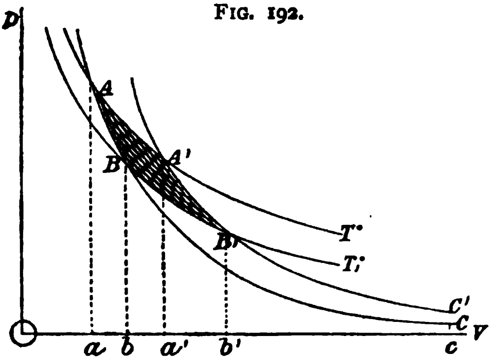
THE *business of a heat engine is to convert heat into work.* This can only be done by allowing heat to pass from a hot body or *source* of heat to some fluid which expands, doing external work, and afterwards allows part of its heat to escape to a cold body, called the *refrigerator.* In every transformation of energy there is more or less waste, and in this case the heat gets readily dissipated to surrounding bodies, tending to bring them all to the same temperature.

If a hot body be placed in contact with a colder one, transference of heat may occur without any work being done. Heat is simply wasted, so far as its power of doing work is concerned, when it passes *directly* in this way by conduction, convection, or radiation to a body of a lower temperature, the heat being no longer available for doing work unless it can pass to another body of still lower temperature. Hence, in order to make the most of the heat received from the source at a high temperature, the working substance must be as nearly as possible at the same temperature, which should remain unchanged whilst the heat is being supplied, and after the temperature of the expanding substance has been reduced to that of the refrigerator, it must remain at this constant temperature during the rejection of part of its remaining store of heat to the refrigerator.

In 1824, SADI CARNOT devised **an ideal perfect heat engine.** The cylinder and piston are supposed to be perfect non-conductors, and the working substance is always either in contact with bodies at its own temperature or enclosed by perfect non-conductors, so that there is no direct transfer of heat, except while the heat is being received from the source or given out to the refrigerator.

*A complete* CYCLE, according to Carnot, *is a series of changes, in which the working substance, after receiving heat, expands, doing work, is compressed, and finally brought back to its original state as regards volume, temperature, and pressure.*

FIG. 192.



Starting with a given mass of a perfect gas enclosed in a cylinder at the initial state A (Fig. 192), Carnot's *cycle of operations* is as follows :—

1. The gas expands along the **isothermal** A A', receiving heat in amount H from the source *at the constant absolute temperature* T, and doing external work. The heat H taken in is represented by the area of the strip C B A A' B' C', bounded by the curve A A', and the two adiabatics A B C, A' B' C' indefinitely produced.

The work done on the piston by the expanding gas is represented by the area *a* A A' *a'*.

2. From A' the gas further expands, doing work, *without gaining or losing heat;* whilst its volume and pressure are given by the **adiabatic** A' B'. At B' its temperature has fallen to $T_1$, that of the refrigerator; and the work done by the gas at the expense of its own heat is represented by the area *a'* A' B' *b'*.

3. Then the gas is compressed at constant temperature

$T_1$ along the **isothermal** B′ B, until its volume and pressure are given by the ordinates of B. While being compressed from B′ to B the gas gives out heat in amount *h* to the refrigerator. This heat is represented by the area of the strip C B B′ C′ bounded by the curve B′ B and the two adiabatics B C, B′ C′ indefinitely produced. The work that has been done on the gas is represented by the area *b*′ B′ B *b*.

Carnot assumed that as water does work in falling from a height to a lower level at which it all flows away, so heat does work in falling from a high temperature to a lower one, the same amount of heat being rejected to the refrigerator as was received by the source, that is, $h = H$. This error does not affect the accuracy of his reasoning if in this third operation we compress, not till $h = H$, but to a point B, so that *adiabatic* or isentropic compression in the fourth operation to the original volume brings the gas back to its original state as represented by the point A.

4. Finally, the gas is compressed from B without allowing any heat to escape until its temperature rises to T; that of the source, when its volume and pressure are given by A, as at the beginning of the first operation. The work done on the gas in thus compressing it along the **adiabatic** B A is represented by the area *b* B A *a*.

The closed figure A A′B′ B is then the *indicator diagram of Carnot's ideal engine.*

**Settling the heat account,** we see that the *gas received from the source, at the higher constant temperature* T, *a quantity of heat* H, represented by the *area* of the strip C B A A′ B′ C′ ... indefinitely produced. At the lower constant temperature $T_1$ the *gas has given out to the refrigerator a quantity of heat h* represented by the *area* C C B′ C′ ... indefinitely produced. No other transference of heat to or from the gas has taken place, and the gas is exactly in its original condition, having the same intrinsic energy as at the start. Therefore, the difference $H - h$, represented by the area A A′ B′ B, has disappeared as heat, and, in fact, has been spent by the gas in doing useful work.

Now the gas in expanding has done external work on the piston, represented by the areas $a$ A A$'$ $a'$ + $a'$ A$'$ B$'$ $b'$; whilst the work that has been spent in compressing the gas is represented by the areas $b'$ B$'$ B $b$ + $b$ B A $a$; so that the difference or area A A$'$ B$'$ B represents the useful work $w$ performed by the engine, neglecting loss by friction. Hence, if J be Joule's equivalent, we have

$$\text{Useful work done } w = \text{J}(\text{H} - h) = \text{area A A}'\text{B}'\text{B}.$$

This cycle can be repeated any number of times, using the same working substance, and thus a continuous supply of work is obtained, whilst heat is let down through an engine from a body at a higher to one at a lower temperature.

Moreover, **this engine is reversible.**

Begin as before with the gas at temperature T and in the state A as regards volume and pressure.

1. Allow the gas to expand along the adiabatic A B, doing external work without gain or loss of heat, till at B the temperature has fallen to $T_{\prime\prime}$ that of the refrigerator.

2. Let it further expand along the isothermal B B$'$, doing useful work, but taking in heat $h$ from the refrigerator at the constant temperature $T_{\prime}$.

3. Compress the gas along the adiabatic B$'$ A$'$, without allowing any heat to escape, till at A$'$ its temperature becomes T that of the source.

4. Further compress the gas, along the isothermal A$'$ A, at constant temperature T, until after giving out heat H to the source, the gas is restored to its original state A.

Therefore, in this reversed order of operations, we see that, on the whole, *work w*, represented by the area A A$'$ B$'$ B, *has to be spent* on the working fluid in taking heat $h$ from the refrigerator and giving out heat H to the source, where the loss H − $h$ is the heat equivalent to the area A A$'$ B$'$ B.

Here work is consumed by the machine which absorbs heat from a body at a lower temperature during isothermal expansion, and rejects it at a higher temperature during isothermal compression, the work spent being proportional to the difference of temperature through which the heat has been raised. In fact, by reversing the cycle of operations in this way, the heat motor engine becomes converted into a refrigerating machine.

CARNOT'S PRINCIPLE.—*In virtue of being reversible the cycle is perfect*, that is, *no engine can perform more work from a given quantity of heat with the same temperatures of source and refrigerator.*

To prove this: Our engine transfers heat H from the source doing useful work $w$, and by our doing work $w$ on the engine, it will transfer heat H to the source. Now, let us *imagine a more perfect engine* working with the same temperatures of source and refrigerator. Let this second engine by transferring heat H do more work than $w$, say $w + w'$. Couple this engine with our engine reversed. We have now this engine working forwards, taking heat H from the source and doing work $w + w'$. Our engine receives work $w$ and gives back heat H to the source. Thus regarding the two engines as one machine, the machine takes no heat from the source and yet does work $w'$ in each cycle of operations. This will go on for ever. But heat must have been spent to perform this work, and this heat can only have come from the *refrigerator*. Hence our machine would continue to do any amount of useful work by taking heat from the coldest body near, and this could go on for ever. This is manifestly absurd, and contrary to all experimental facts, for, as Sir William Thomson puts the axiom :—"It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects." Therefore, no engine can be *more* efficient than Carnot's reversible one.

It follows that all engines with perfect reversible cycles, and working between the same temperatures of source and refrigerator, have the same efficiency, whether air or other gas be used in them ; hence *the efficiency of a reversible engine is independent of the nature of the working substance, and*

***depends only on the temperatures at which heat is taken in and given out.***

If the absolute temperature T be divided into any number of equal parts, a reversible engine may be constructed by combining a great number of reversible engines of small ranges working between these temperatures, the refrigerator of one being the source of the next, then the work performed by each of these would be equal. This may be seen even more clearly by dividing the isothermal A A′, Fig. 192, into a number of equal parts by equidistant adiabatics drawn between A B C and A′ B′ C′, also isothermals for each degree of temperature, so that each of the little curvilinear areas formed represents a unit of heat. If H denotes the quantity of heat taken from the source at the absolute temperature T, and $h$ denotes the heat given out by the working substance to the refrigerator at temperature $T_{,,}$ then by Thomson's definition of absolute temperature we have

$$\frac{H}{T} = \frac{h}{T_{,}} = \frac{H-h}{T-T_{,}},$$

therefore

$$\frac{H-h}{H} = \frac{T-T_{,}}{T}.$$

Now the useful work $w$, done on the piston is given by the equation

$$w = J\,(H-h) = J\,H\left(1-\frac{h}{H}\right) = J\,H\left(1-\frac{T_{,}}{T}\right);$$

therefore

$$\text{work done, } w = J\,H\left(\frac{T-T_{,}}{T}\right).$$

With $T_{,} = 0$ the work done $= J\,H$, and hence *all the sensible heat* which leaves the source would be converted into work. Now from the quantity of heat H we cannot possibly have more work than this performed, hence $T_{,}$ can never become negative, and in fact, the zero of this scale is the absolute zero of temperature.

It is impossible to make $T_{,} = 0$, even with our ideal perfect engine, for, as we have seen above, this would require infinite expansion and a corresponding cylinder infinitely long.

We are thus led to the

SECOND LAW OF THERMO-DYNAMICS :—

**The Law which governs the Transformation of Heat into Work,** *and tells us the greatest fraction of the total heat given to any heat engine that can be converted into work done on the piston.* This ratio, $\frac{w}{JH}$, called the *ideal efficiency of a perfect heat engine,* is

$$\frac{T - T_{,}}{T} = 1 - \frac{T_{,}}{T},$$

where T stands for the absolute temperature of the source, and $T_{,}$ that of the refrigerator.

This is the *greatest possible efficiency of any heat engine working between these temperatures,* and we see that it depends only on the difference between the two limiting temperatures. The greater the difference of temperatures we can command, *other things being equal,* the greater the efficiency.

Now the **conditions** necessary to attain this ideal of perfection in any heat engine are :—

1. The source of heat should be at the highest temperature of the working fluid in the cylinder, but no higher, whilst the fluid only receives heat at this high constant temperature T.

2. The refrigerator or condenser should be at the lowest temperature of the working fluid, whilst the fluid only allows heat to escape at this lower constant temperature $T_{,}$.

3. At all other temperatures the fluid should neither receive nor give out heat.

In other words, the working fluid must (*a*) receive and reject heat only *at constant temperatures,* that is, during the *two isothermal operations ;* (*b*) the two intermediate operations must be *adiabatic or isentropic*, so that as much work is done *on* the fluid during the one operation as *by* it during the other, whilst changing from the higher to the lower temperature.

Obviously the foregoing conditions cannot be satisfied in an actual engine, especially not in the combustion engine cylinder with large cooling surfaces surrounded by water. First the working fluid actually receives heat, not at any one temperature alone, but at all points from the moment of ignition until it is rejected to the atmosphere by the exhaust. Nor is the whole heat rejected at the temperature of the atmosphere. There is loss of heat by the working fluid, at all temperatures, through the walls of the cylinder to the water-jacket. The amount of heat thus lost is greatest at the high temperatures. This arrangement, with waste of heat to the cooling water, is one structural defect of the modern gas engine; another great waste of heat takes place in the rejection of the working fluid to the exhaust at a high temperature with a large quantity of heat. Besides, the range of temperature is thus cut short, and the efficiency diminished accordingly. From this point of view it is clearly advisable to lower the temperature at which the heat is rejected by long expansion, and on this account initial compression of the gaseous mixture before ignition is also most important with high piston speed.

It follows that it is unfair to compare the actual efficiency of the internal combustion engine with that of a perfect heat engine working between the limits of the highest temperature reached during combustion and the ordinary atmospheric temperature. However, the different cycles of actual heat engines may be compared by calculating the work done during the different operations in each, having determined the laws of expansion or compression from the curves of their indicator diagrams. In this way we shall further study the

### *Ideal Indicator Diagrams*

of different types of internal combustion engines (page 496).

To start with, let us consider more particularly the *indicator diagram and the behaviour of the working fluid in the cylinder of* **Carnot's Ideal Perfect Engine.**

Imagine a piston to be one square inch in sectional area. Let the pressure of the fluid filling the space in the cylinder behind the piston be $p$ lb. per square inch measured from perfect vacuum, and assume no pressure on the other side of piston. The total pressure on the piston is $p$ lb. Now if the piston moves out $l$ feet the work done is $p\,l$ foot-pounds, that is, provided the pressure remains constantly $p$ lb.

Suppose the diameter of the cylinder to be $d$ inches, then the cross sectional area of the piston is $\frac{\pi d^2}{4} = \cdot 7854\, d^2 = \mathrm{A}$ square inches (say). There is a pressure of $p$ lb. on every square inch, and therefore on A square inches the total pressure is $\mathrm{A}p$ lb.

Distances passed through by the piston are expressed in feet. The volume occupied by the fluid will be given as lengths of the cylinder of uniform sectional area. The clearance, ports, and spaces in the cylinder behind the piston are sometimes considerable. In such cases represent the cylinder a little longer on the diagram, in order to take into account the volume of these passages expressed in terms of length of cylinder.

As the piston moves forward through a very small distance, ·0001 ft., the pressure of the fluid may fall to $p'$ lb. per square inch. The work done on the piston is less than $\mathrm{A}p \times \cdot 0001$ foot-lb. and more than $\mathrm{A}p' \times \cdot 0001$ foot-lb. It is accurately determined by finding the average pressure $p$ lb. per square inch during an infinitely small movement of the piston through an exceedingly short length $dl$ ft. of the cylinder. The work done by the fluid in driving the piston through this length $dl$ ft. is

$$\mathrm{A}\,p\,dl \text{ foot-pounds.}$$

Then, to find the total work done, we take the sum of a great number of such terms when we know the law of variation of the pressure and volume.

### *Work done during an Isothermal Operation.*

For the **isothermal operation** along A B in the indicator diagram A B C D (Fig. 193) of Carnot's ideal engine, the law is

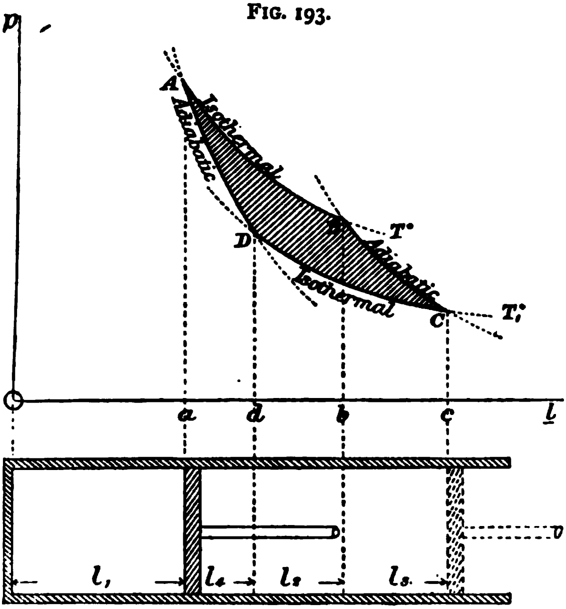
$$p\,l = \text{constant } k,$$

so that

$$p = \frac{k}{l}.$$

Let O$a$ = $l_1$ feet, the distance of piston from end of cylinder, represent the volume occupied by the working fluid at the beginning of the stroke; and O$b$ = $l_2$, the volume to which it has expanded, whilst $p_1$ and $p_2$ are the corresponding pressures at constant absolute temperature T.

FIG. 193.



The whole work $W_{1,2}$. foot-lb. done by the fluid in driving the piston from $l_1$ to $l_2$ will be represented by the area $a\,A\,B\,b$, which is the limit of the sum of all such terms as $A\,p\,dl$, as the number of steps between $l_1$ and $l_2$ is indefinitely increased. (See page 240.)

This limit is denoted by the integral

$$\int_{l_1}^{l_2} A\,.\,p\,.\,dl. = A\int_{l_1}^{l_2} p\,.\,dl,$$

substituting the value $\frac{k}{l}$ for $p$, we have

$$W_{1,2.} = A\int_{l_1}^{l_2} \frac{k}{l}\,.\,dl = A\,k\log_e\frac{l_2}{l_1}.$$

But the isothermal law is

$$l_1 p_1 = l_2 p_2 = k,$$

therefore

$$W_{1,2.} = A\,l_1 p_1 \log_e\frac{l_2}{l_1} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

This is the rule* for finding the work done by the fluid on the piston during the isothermal operation.

If H be the quantity of heat received by the fluid to keep up this constant temperature while work is being done, we know by the law of equivalence that

$$W_{1,2.} = J\,.\,H,$$

where J is Joule's mechanical equivalent of heat, or 1390; then

$$H = \frac{A}{J}\,.\,l_1 p_1\,.\log_e\frac{l_2}{l_1}.$$

*Example* 1.—A piston 12 inches in diameter is moved by the pressure exerted only by gas inside the cylinder.

If the pressure is 80 lb. per square inch when the gas occupies 1 foot length of cylinder, how much work will be done by the gas, kept at *constant temperature*, in driving the piston to a distance of 3 feet from the end of cylinder?

---

* Multiply ordinary logarithms (to the base 10) by 2·30261 to convert them into the Naperian or hyperbolic logarithms used in this formula.

we get the work done by the fluid on the piston,

$$A\, l_1 p_1 \log_e \frac{l_2}{l_1} = 113{\cdot}1 \times 1 \times 80 \times \log_e \frac{3}{1}$$

$$= 113{\cdot}1 \times 80 \times 1{\cdot}0986 = 9940 \text{ ft.-lb.}$$

## Adiabatic Operation, B C.

In the next operation, B C, Fig. 193, the piston is move from the position O $b = l_2$ feet, where the expanding fluid is pressure $p_2$ and absolute temperature T, to the position O $c =$ feet, whilst the fluid has fallen in pressure to $p_3$ and temperatu $T_1$. The cylinder and piston enclosing the gas are suppose to be perfect non-conductors, so that there is no transmissio of heat to or from other bodies, and the gas expands, doin work on the piston at the expense of its own intrinsic energ consequently its temperature falls from T to $T_1$.

These changes are adiabatic and follow the law

$$p\, l^{\gamma} = \text{constant},$$

where $\gamma$ is the ratio of the specific heat of the working gas a constant pressure to that at constant volume.

In the case of dry air, $\gamma = 1{\cdot}409$, and its value must b calculated for every different gas or mixture employed.

The law of expansion may also be found directly from the curve, as shown above (page 430), and the value of $x$ used instead of $\gamma$.

We have

$$p\, l^{\gamma} = \text{constant} = p_2\, l_2^{\gamma},$$

so that

$$p = \frac{p_2\, l_2^{\gamma}}{l^{\gamma}}.$$

The work $W_{2,3}$. done by the fluid on the piston, in moving it from $l_2$ to $l_3$, is represented by the area $b$ B C $c$ (Fig. 193), and

$$W_{2,3}. = A\int_{l_2}^{l_3} p \,.\, dl = A\int_{l_2}^{l_3} \frac{p_2\, l_2^{\gamma}}{l^{\gamma}}\, dl$$

which becomes

$$A p_2 l_2^\gamma \int_{l_2}^{l_3} \frac{dl}{l^\gamma} = \frac{A p_2 l_2^\gamma}{\gamma - 1} \left\{ - \frac{1}{l_3^{\gamma-1}} + \frac{1}{l_2^{\gamma-1}} \right\},$$

$$= \frac{A p_2}{\gamma - 1} \left\{ - \frac{l_2^\gamma}{l_3^{\gamma-1}} + l_2 \right\},$$

hence

$$W_{2,3.} = \frac{A p_2 l_2}{\gamma - 1} \left\{ 1 - \left(\frac{l_2}{l_3}\right)^{\gamma-1} \right\} \quad . \quad . \quad . \quad (2)$$

Now in this adiabatic operation,

$$p_3 l_3^\gamma = p_2 l_2^\gamma,$$

and at the same time

$$\frac{p_3 l_3}{T_1} = \frac{p_2 l_2}{T}$$

since the fluid is a perfect gas.

Divide these quantities on both sides of these equations and we have

$$l_3^{\gamma-1} T_1 = l_2^{\gamma-1} T,$$

therefore

$$\left(\frac{l_2}{l_3}\right)^{\gamma-1} = \frac{T_1}{T} = \frac{p_3 l_3}{p_2 l_2}.$$

Substituting these values, equation (2) becomes

$$W_{2,3.} = \frac{A}{\gamma - 1} (p_2 l_2 - p_3 l_3). \quad . \quad . \quad . \quad (3)$$

To express this work done in terms of $p_1$, $l_1$, and the temperatures T, $T_1$, we must bear in mind that

$$p_1 l_1 = p_2 l_2$$

along the same isothermal,

and

$$\frac{p_1 l_1}{T} = \frac{p_3 l_3}{T_1},$$

since we are dealing with the same mass of perfect gas, so that

$$p_3 l_3 = p_1 l_1 \frac{T_1}{T},$$

and therefore

$$p_2 l_2 - p_3 l_3 = p_1 l_1 - p_1 l_1 \frac{T_1}{T},$$

thus

$$W_{2,3.} = \frac{A}{\gamma - 1} \cdot p_1 l_1 \left(1 - \frac{T_1}{T}\right),$$

or

$$W_{2,3.} = \frac{A}{\gamma - 1} . p_1 l_1 . \frac{T - T_1}{T} \quad . \quad . \quad . \quad . \quad (4)$$

These rules, (2), (3), and (4), give the work done by the fluid on the piston from position $l_2$ to $l_3$ along the adiabatic, and they are true for any gaseous mixture whatsoever.

Formula (2) holds generally when the law connecting $p$ and $l$ is known, but rule (3) is more convenient, and gives the work done in every case, except when $\gamma = 1$, for then the law is $p\,l = k$ and $p_2 l_2 = p_3 l_3$, which gives an indeterminate expression.

In this case the work done is calculated by rule (1).

*Example* 2.—Suppose the law of expansion to be $p\,l^{1.6}$ = constant. If $p_2 = 130$ lb. when $l_2 = 2$ feet, find the work done by the gas in driving the piston through 1·3 feet. The effective area of the piston exposed to the pressure is 100 square inches.

*Answer.*—

Here

$$130 \times 2^{1\cdot6} = p_3 \times (3\cdot3)^{1\cdot6},$$

whence

$$p_3 = 130\left(\frac{2}{3\cdot3}\right)^{1\cdot6},$$

that is

$$p_3 = 130 \times 0\cdot4718 = 61\cdot33.$$

Substituting these values in formula (3) gives

$$\text{Work done} = \frac{A}{\gamma - 1}\left( p_2 l_2 - p_3 l_3 \right)$$

$$= \frac{100}{0{\cdot}5}\left(130 \times 2 - 61{\cdot}33 \times 3{\cdot}3\right),$$

$$= 200\left(260 - 202{\cdot}4\right) = 200 \times 57{\cdot}6.$$

Therefore the work done is 11,520 foot-pounds.

## Isothermal Operation, C D.

Starting at C with $p_3$, $l_3$, and the lower temperature $T_1$, if we compress the gas rapidly its temperature would rise, but the cylinder is supposed to be in contact with a refrigerator, to which the gas gives away some heat, and so remains at constant temperature $T_1$.

Under these circumstances, what work will be done by the piston in compressing the gas to D, where the pressure and volume are $p_4$ and $l_4$ respectively?

It will be just the same as what would be done by the gas on the piston whilst expanding along the isothermal from D to C, that is, from position $l_4$ to $l_3$ in the cylinder; so that rule (1) gives us the amount of work done in compressing the gas. This is negative work, because done *on the gas*, and is to be subtracted from the total work done on the piston by the expanding gas.

Applying rule (1), within the limits $l_3$ and $l_4$,

we find $$W_{3,4.} = - A \,.\, p_4 \, l_4 \,.\, \log_\epsilon \frac{l_3}{l_4}.$$

To express this in terms of $p_1$, $l_1$,

we have $$\frac{p_4 l_4}{T_1} = \frac{p_1 l_1}{T}, \quad \text{or} \quad p_4 l_4 = p_1 l_1 \,.\, \frac{T_1}{T}. \quad . \quad . \quad (a)$$

Also

$$p_4 l_4^{\gamma} = p_1 l_1^{\gamma},$$

divide this by ($a$) gives

$$\left.\begin{array}{l} l_4^{\gamma-1} = l_1^{\gamma-1} \dfrac{T}{T_1}. \quad . \quad . \quad (\beta) \\ \text{Similarly} \\ l_3^{\gamma-1} = l_2^{\gamma-1} \dfrac{T}{T_1}. \quad . \quad . \quad . \end{array}\right\} \text{Hence } \frac{l_3}{l_4} = \frac{l_2}{l_1}.$$

so that

$$W_{3,4.} = -A.p_1 l_1.\frac{T_1}{T} \log_e \frac{l_2}{l_1}. \quad . \quad . \quad . \quad (5)$$

This is the rule for calculating the work done by the piston on the fluid in compressing it from $l_3$ to $l_4$, whilst it gives away heat $h$ to the refrigerator at constant temperature $T_1$.

Here $W_{3,4.} = J\,h$,
and therefore the *amount* of heat $h$ rejected to the refrigerator is given by the equation,

$$h = \frac{1}{J}\frac{T_1}{T}\left(A\,p_1\,l_1 \log_e \frac{l_2}{l_1}\right).$$

## Adiabatic Operation, D A.

The gas is still further compressed from $l_4$ to $l_1$, but this time it is allowed to retain all the heat generated by the adiabatic compression which has been commenced at the point D, such that the high initial temperature T and pressure $p_1$ are reached at the same time as the original volume $l_1$.

The work is done by the piston on the gas, and is therefore to be considered negative. The amount is found by applying rule (2) for the limits $l_4$ and $l_1$; thus

$$W_{4,1.} = -\frac{A}{\gamma - 1} p_4 l_4 \left\{\left(\frac{l_4}{l_1}\right)^{\gamma - 1} - 1\right\},$$

but from the equations ($\alpha$) and ($\beta$) we have

$$p_4 l_4 = \frac{T_1}{T} \cdot p_1 l_1, \quad \text{also} \quad \left(\frac{l_4}{l_1}\right)^{\gamma - 1} = \frac{T}{T_1},$$

hence the above expression becomes

$$W_{4,1}. = -\frac{A}{\gamma - 1} \cdot p_1 l_1 \cdot \frac{T_1}{T}\left(\frac{T}{T_1} - 1\right),$$

or

$$W_{4,1}. = -\frac{A}{\gamma - 1} \cdot p_1 l_1 \cdot \frac{T - T_1}{T} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This only differs in sign from formula (4) above, which gives the work done in the other adiabatic operation B C, hence the areas *a* A D *d* and *b* B C *c* are equal.

The working fluid is now in its initial state, and has thus gone through a *complete cycle of operations.*

It received heat H from the source at the higher temperature T, and gave out heat *h* to the refrigerator at the lower temperature $T_1$, hence the difference H − *h is the amount of heat that has been transformed into mechanical work done on the piston.*

From the values of H and *h* given above in the two isothermal operations we find by division

$$\frac{H}{h} = \frac{T}{T_1}.$$

This is a most important result, being the basis and expression of the **absolute scale** of temperature, defined by Sir William Thomson as follows:—"*The absolute values of two temperatures are to one another in the proportion of the heat taken in to the heat rejected in a perfect heat engine, working with a source and refrigerator at the higher and lower of the temperatures respectively.*" *

The expression may be written in another form

$$\frac{H}{T} = \frac{h}{T_1}, \quad \text{or} \quad \frac{H}{T} - \frac{h}{T_1} = 0 .$$

---

* See *Trans. R.S.E.*, May 1854.

cycle, that is, the sum of all the quantities

$$\sum \frac{H}{T} = 0.$$

To *sum up* the **account of work done** *on and by the fluid* in these four operations whilst the piston moves successively to the positions 1, 2, 3, 4, under the above conditions, we have

Isothermal A B .. $W_{1,2}. = A.p_1 l_1.\log_\epsilon \frac{l_2}{l_1}$ ft. lb. work done *on* piston.

Adiabatic B C .. $W_{2,3}. = \frac{A}{\gamma - 1} . p_1 l_1 . \frac{T - T_1}{T}$ ,, *on* ,,

Isothermal C D .. $W_{3,4}. = - A.p_1 l_1 . \frac{T_1}{T} \log_\epsilon \frac{l_2}{l_1}$ ,, *by* ,,

Adiabatic D A .. $W_{4,1}. = - \frac{A}{\gamma - 1} .p_1 l_1 . \frac{T - T_1}{T}$ ,, *by* ,,

This represents the total work done on and by the piston during the four operations.

Obviously the two adiabatics cancel out.

This leaves the actual work, got out of the total heat H supplied to the engine, to be the difference between the work done on the piston along the higher isothermal A B and that done by it in compressing the gas at the lower temperature $T_1$.

Hence the *useful work done on the piston by the gas* and given out by the engine in the complete cycle is

$$A p_1 l_1 \log_\epsilon \frac{l_2}{l_1} - A p_1 l_1 \frac{T_1}{T} \log_\epsilon \frac{l_2}{l_1},$$

$$= A p_1 l_1 \log_\epsilon \frac{l_2}{l_1} \left(1 - \frac{T_1}{T}\right) \text{ foot-pounds.}$$

The *total energy supplied to the gas as heat* at the higher temperature is

$$A\, l_1 p_1 \log_\epsilon \frac{l_2}{l_1} \text{ foot-pounds.}$$

Therefore the *efficiency of this ideal perfect heat-engine* is

$$\frac{H - h}{H} = 1 - \frac{T_1}{T} = \frac{T - T_1}{T}.$$

## EFFICIENCY OF PRACTICAL HEAT ENGINES.

In the **steam engine** the highest temperature of the steam entering the cylinder seldom exceeds 195° C., and the temperature of the condenser is about 45° C.

Consequently the greatest possible efficiency is

$$\frac{T - T_1}{T} = \frac{468 - 318}{468} = \frac{150}{468} = 0 \cdot 32.$$

That is, an absolutely perfect heat engine working between these temperatures could only convert one-third of the heat supplied to it into useful work. This is the limit of possible efficiency, set by the law of transformation for any heat engine working within this range of temperature.

Even this is far from being realised practically.

Of the total heat of combustion of the fuel there is great waste in the furnace by hot ashes, unburnt fuel, and gases, as well as heat lost by radiation and the large amount expended in raising the temperature of the furnace gases, displacing the atmosphere to produce draught. It is also difficult to conduct the heat from the fire to the water, owing not so much to the thickness of the metal plates as to there being two surfaces of iron and water, of which the emissivity and conductivity are small, whilst the resistance to flow of heat is considerable.

Then again, a great amount of heat is absorbed by the water, as latent heat of evaporation, in merely changing it into steam. A portion of this may be recovered by condensation in large engines, but in small ones it is all rejected.

A perfect engine working between 195° C. and 100° C. would have an efficiency of 0·20. But the loss of heat, during its transmission from the boiler to the cylinder, increases very rapidly with the pressure of steam at temperatures above 150° C., so that high temperatures cannot be employed without inconvenient pressures and the dangers of explosions, injury to cylinder, lubricants, and packing.

Besides, to produce the lower temperature there is the friction of the pumps and other moving parts.

All these reduce the combined efficiency of the furnace, boiler, and engine as given by the consumption of fuel per indicated horse-power, to 0·12 in large powers of steam engine, whilst it rarely exceeds 0·04 in small ones.

A good Paxman portable compound horizontal steam engine, at the Society of Arts Trials (1888), gave 21·55 indicated horse-power, and 18·95 brake horse-power, whilst the amount of coals used per hour per indicated horse-power was at the rate of 1·89 lb. and per brake horse-power 2·15 lb. In the case of the indicated work, this means that 9·6 per cent. of the available heat units, given by the consumption of fuel per horse-power, was turned into work by the engine and boiler combined.

In point of fact these figures would be considered highly satisfactory if always obtained in ordinary working.

Carnot's *ideal engine* cooled the working fluid from T to $T_1$ by allowing it to expand along B C, Fig. 194, doing work at the expense of its own heat, and exactly the same amount of heat was restored to the gas in compressing it along D A in order to warm it from $T_1$ to T.

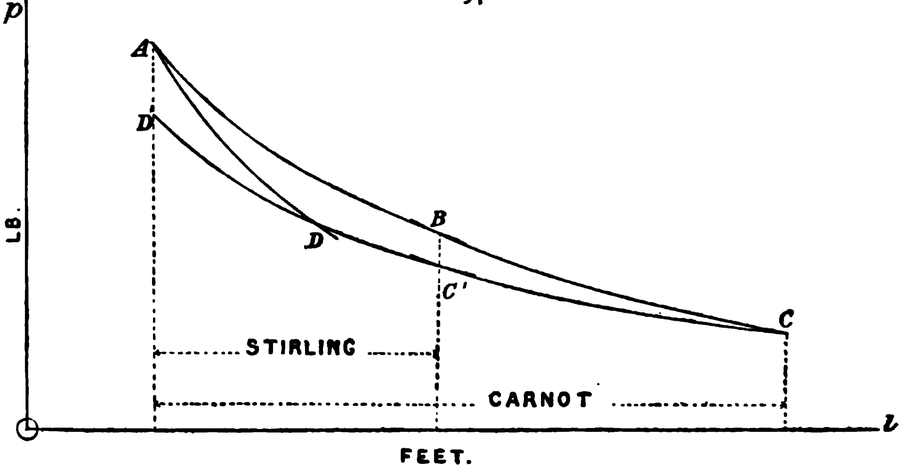
In Stirling's *actual* **hot-air engine** the temperature is reduced by allowing the gas to pass through a regenerator which absorbs and stores up the heat in the operation B C′, and this amount of heat is restored directly as heat along D′ A, while the gas returns through the regenerator. The area of the Stirling diagram A B C′ D′ A, Fig. 194, is equal to that of Carnot A B C D, and the Stirling cycle of operations is perfect and reversible, whilst the device of the regenerator greatly reduces the length of cylinder and travel of piston.

Stirling's *hot-air engine* worked between the temperatures 343° and 65° C. Therefore, the maximum theoretical efficiency was

$$\frac{T - T_1}{T} = \frac{343 - 65}{343 + 273} = \frac{278}{616} = 0{\cdot}45.$$

The actual efficiency really attained was about 0·16. This good result was greatly reduced by the bad furnace arrangements. The furnace was kept at a much higher temperature than could be utilised. There was no effective method of heating a large mass of air quickly to get sufficiently high pressure. The available mean pressures in the cylinder were very low.

FIG. 194.



In the "Ericsson" air engine there was only a pressure of 3 lb. per square inch, which is very small compared with that in steam engines. Air engines were, therefore, very large for a given power. The working parts, and especially the cylinder bottoms, were burnt out quickly. There was very great waste of the total heat of combustion of the fuel; whilst in forms like the "Cayley-Buckett" and Jenkin's engine, the intensely heated air always burnt and destroyed the valves, ports, and pipes through which it passed.

These engines never came into very general use, because they were cumbersome and expensive. However, hot-air engines are still made for small powers, but their latest development, the internal combustion engine, has proved more successful and convenient as a prime motor.

Considered as a heat engine, the main cause for the great efficiency of the modern **Internal Combustion Engine** is the *furnace arrangement*—the way in which the fluid is heated. The charge, consisting of an explosive mixture of gas and air, is compressed in the working cylinder behind the piston, and thereby raised to a high temperature and pressure. This facilitates ignition, and the interaction or combination is so rapid as to get an explosion. The whole energy or heat of combustion is in the gas itself. *Each particle of gas is a little furnace giving out heat of its own.* A large proportion of this heat is serviceable, and can be utilised as the piston is driven forward by the burning and expanding gas.

For a moment after ignition a temperature of 1800° C. may probably be attained. Various causes rapidly reduce this to about 1600° C., and the gases are gradually burned as they are allowed to expand by the forward motion of the piston, until rejected by the exhaust at a temperature about 400° C.

The efficiency of a perfect heat engine working with this range of temperature cannot be higher than

$$\frac{T - T^1}{T} = \frac{1200}{1873} = 0{\cdot}64.$$

It is found in actual practice that with an imperfect cycle and all practical losses, about 23 per cent. of the whole heat of combustion of the gas is turned into work in the best internal combustion engines. In fact, it has been proved that a good gas engine worked with cheap producer gas can do 1 horse-power with a consumption of coal less than half that required in the best steam engines of the same power.

There is still much room for improvement, seeing that 27 per cent. of the heat is carried away by the jacket-water, and the remaining 50 per cent. rejected in the exhaust gases and otherwise unaccounted for. These drawbacks may be partly overcome by some happy application of the regenerator principle. However, practical considerations indicate that although this engine may far surpass the steam engine in efficiency, yet a heat engine with an imperfect but workable cycle can never attain the efficiency of the ideal perfect engine working between the same limiting temperatures. Considered as a piece of mechanism, the gas engine is now far inferior to the steam engine.

## IDEAL INDICATOR DIAGRAMS.

Some idea of the possible efficiency of the various imperfect cycles of practical engines may be gathered from a consideration of the ideal performance of each cycle under conditions that we can never hope to obtain in practice, and which, unfortunately, do not equally affect all the types of gas engine.

The following assumptions are made :—

1. The combustion takes place instantaneously, and the whole heat is developed at once at constant volume, there being no further burning.

2. There is no loss of heat to the water jacket or cylinder.

3. The working fluid behaves as a perfect gas, and expands according to the adiabatic law.

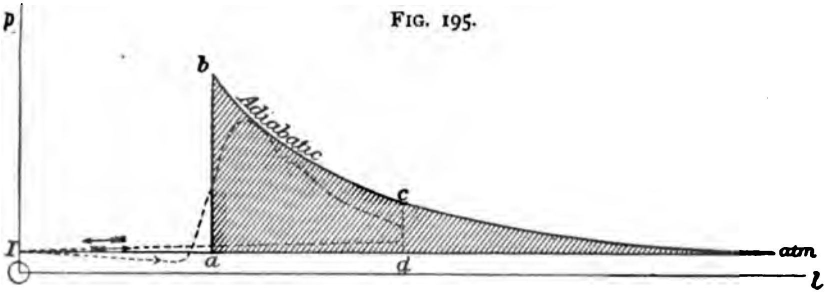
4. The charge is admitted to the cylinder at atmospheric pressure, and the exhaust valve opens at the very end of the stroke, the products of combustion being rejected to the atmosphere without resistance.

We must bear in mind that the hypothetical diagrams calculated in this way are not the same shape as the real indicator diagrams, shown in broken lines, as taken from the actual engines.

It will be most convenient for us to follow the same order and classification as given above in Chapter VI.

*First Type.*—In the ideal cycle of this engine represented by diagram (Fig. 195), the piston in its forward motion draws

FIG. 195.



in after it the charge of gas and air at atmospheric pressure and temperature $T_0$ to position *a*, combustion with instantaneous heating of H units takes place at *a b* constant volume to temperature T, followed by adiabatic expansion *b c* to atmospheric pressure, then the products with *h* heat units are rejected at temperature $T_1$ during the return stroke of the piston.

Here the heat supplied by the explosion of suppose unit weight of charge at constant volume is

$$H = C_v(T - T_0),$$

and that rejected at constant atmospheric pressure is

$$h = C_p(T_1 - T_0),$$

where $C_v$ and $C_p$ stand for the specific heats of the working fluid at constant volume and at constant pressure respectively.

We have therefore the efficiency

$$\frac{H - h}{H} = \frac{C_v(T - T_0) - C_p(T_1 - T_0)}{C^v(T - T_0)}.$$

but $\frac{C_p}{C_v} = \gamma$, therefore

$$\text{Efficiency} = 1 - \gamma . \frac{T_1 - T_0}{T - T_0},$$

also

$$\frac{T_1}{T_0} = \left(\frac{T}{T_0}\right)^{\frac{1}{\gamma}},$$

since it is the adiabatic operation of a perfect gas (page 486), and the pressure varies directly as the absolute temperature. Thus $T_1$ is known.

Taking the famous **Lenoir** as the representative of this type, the ideal indicator diagram would be *a b c d*, whilst the real diagram given in dotted lines with the sharp corners rounded off, shows that the charge is drawn in at pressure less than atmospheric the rise or slope of the explosion line, corresponding to *a b*, indicates gradual combustion, and therefore *not* at constant volume since the piston is moving; moreover, the products are discharged at a pressure higher than atmospheric.

It is very easy to calculate the efficiency from the ideal diagram *a b c d* formed of the adiabatic *b c* and straight lines, if we assume that the working substance behaves as a perfect gas.

We have simply to find the total energy E of the explosion, that is, the energy given to the gas, and the total work $w$ done by it; then the

$$\text{Efficiency} = \frac{w}{E}.$$

In the position *a*, take—

Temperature, $T_0 = 17°$ C. or $290°$ absolute
Pressure, $p_0 = 15$ lb. per sq. in. (atmospheric),
Length of cylinder, $l_0 = 1$ foot.

Now the fluid is to follow the law $\frac{pl}{T} = k$,

and, in this case, $k = \frac{15}{290}$.

Assume the highest temperature reached at the point *b*,

$$T = 1537° \text{ C. or } 1810° \text{ absolute.}$$

By rule (4), page 487, the stuff has received energy

$$E = \frac{A}{\gamma - 1} k (T - T_0).$$

and pressure fall until twice the volume, $l_1 = 2$ feet, is reached at *c*, when the temperature $T_1$ is 1360° absolute. The work done in this forward part of the stroke is

$$\frac{A}{\gamma - 1} \cdot k\,(T - T_1).$$

From this amount we have to deduct the work done by the piston in driving out the products in the backward stroke *d a* from $l_1$ to $l_0$, that is

$$p_0\,A\,(l_1 - l_0).$$

Hence the effective work done by the fluid on the piston in one cycle is

$$w = \frac{A}{\gamma - 1} k\,(T - T_1) - p_0\,A\,(l_1 - l_0)\,;$$

and the efficiency

$$\frac{w}{E} = \frac{(T - T_1) - p_0 \cdot \frac{\gamma - 1}{k} \cdot (l_1 - l_0)}{T - T_0} \quad \ldots\ldots \quad (2)$$

Suppose, for the mixture of gas and air used, $\gamma = 1{\cdot}37$, so that the law of expansion along the curve *b c* is

$$p\,l^{1.37} = \text{constant}.$$

Substitute the given values and we find

$$\text{Efficiency} = \frac{w}{E} = \frac{450 - 15 \times \frac{290}{15} \times {\cdot}37 \times 1}{1520} = 0{\cdot}225$$

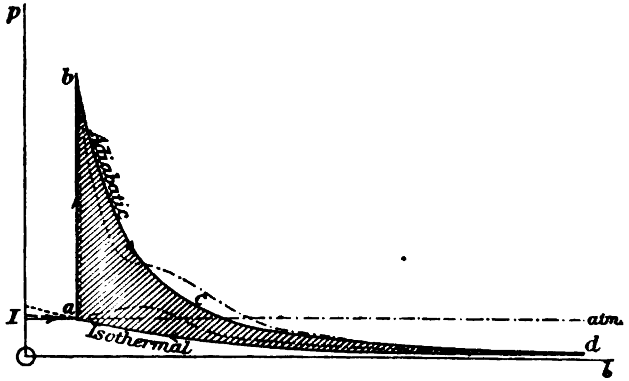
It will be found from equation (2) that the efficiency may be slightly increased by a higher explosion temperature T and using a longer cylinder. However, these figures are far from being realised in practice.

### CLASS I.—*Second Type.*

## **Atmospheric Engines.**

The ideal diagram *a b c d* is shown in Fig. 196, and the real one of the Otto and Langen engine indicated by the dotted curves.

FIG. 196.



The explosive charge, introduced into the cylinder during the first part $l_0$ of the stroke at atmospheric temperature $T_0$ and pressure $p_0$, is fired at *a*, and the maximum temperature T and pressure *p* developed at constant volume as represented by the point *b*.

Then the free piston is projected upwards by the gases with great velocity along the adiabatic *b c d* until brought to rest by gravity, friction, and atmospheric pressure, when the temperature of the products have been reduced to $T_0$ at position $p_1, l_1$. During this adiabatic operation the work expended on the piston, in raising it, is

$$\frac{A}{\gamma - 1}(p\,l_0 - p_1\,l_1).$$

During the return stroke the piston, thrown into gear with driving shaft, comes down gradually under the pressure of the atmosphere and the action of gravity, slowly compresses the burnt products along the isothermal *a a*, and finally expels them at atmospheric pressure. The work done by the piston on the stuff along this isothermal is

$$A p_0 l_0 \log_e \frac{l_1}{l_0}.$$

Hence

$$\text{Efficiency} = \frac{\frac{A}{\gamma - 1}(p l_0 - p_1 l_1) - A p_0 l_0 \log_e \frac{l_1}{l_0}}{\frac{A}{\gamma - 1}(p l_0 - p_1 l_1)}$$

$$= 1 - \frac{(\gamma - 1) p_0 l_0 \log_e \frac{l_1}{l_0}}{p l_0 - p_1 l_1}.$$

But since *a d* is isothermal

$$p_1 l_1 = p_0 l_0.$$

We have also (see page 489)

$$\left(\frac{l_1}{l_0}\right)^{\gamma - 1} = \frac{T}{T_1} = \frac{p}{p_0},$$

so that

$$\frac{l_1}{l_0} = \left(\frac{T}{T_1}\right)^{\frac{1}{\gamma - 1}}.$$

The above expression becomes

$$\text{Efficiency} = 1 - \frac{(\gamma - 1) p \log_e \frac{l_1}{l_0}}{p - p_0}$$

$$= 1 - \frac{(\gamma - 1) T_1 \log_e \left(\frac{T}{T_1}\right)^{\frac{1}{\gamma - 1}}}{T - T_1} \quad . \quad . \quad . \quad (3)$$

As in the previous example, take

Highest temperature, $T = 1537°$ C., or 1810° absolute
Atmospheric „ $T_1 = 17°$ C. „ 290° ,

also

$$\gamma = 1\cdot 37$$

and we have

$$\text{Efficiency} = 1 - \frac{0\cdot 37 \times 290 \times 4\cdot 94}{1520} = 0\cdot 65.$$

This extremely high efficiency can only be obtained by very great expansion, to about 100 times the original volume, and by exceedingly high speed of piston during part of its upward flight as a projectile, with great noise and vibration from the recoil reaction upon firing the charge, which necessitates a large cumbersome machine, whilst the actual rate of working due to the downward motion of piston is comparatively slow.

It is very difficult to take an actual diagram from such an engine, and the curve is usually of a very doubtful character when found. The energy of the explosion is rapidly stored up in the freely moving piston as energy of motion before there is time for much loss by cooling. The engine is very efficient and has given economical results in practice, but the efficiency as calculated above is only imaginary.

## CLASS II.—ENGINES WITH COMPRESSION.

*First Type.*—The ideal indicator diagrams of the cycles of operations in engines of this type are shown in Fig. 197.

In the most perfect engine the mixture of gas and air is drawn in during the operation 1*a*, under constant atmospheric pressure and temperature, so that position *a* is $p_2$, $l_2$, and $T_2$ absolute.

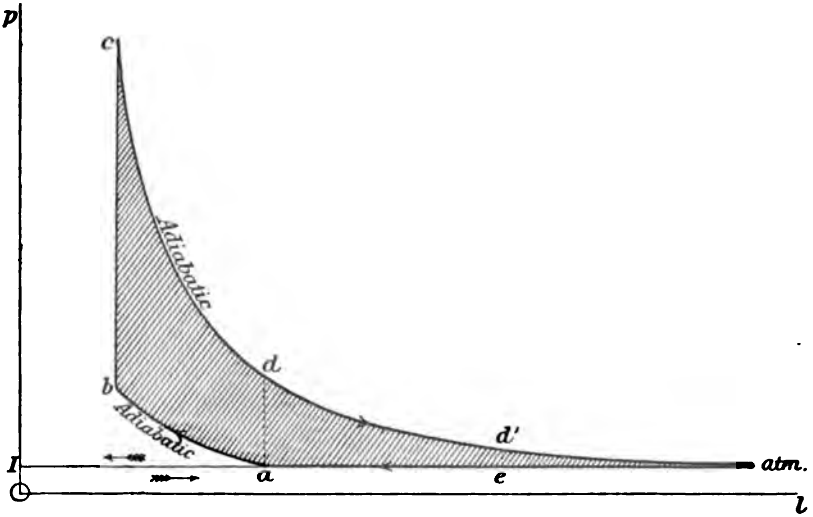
In the next operation, the charge is compressed along the adiabatic *a b*, either in a pump cylinder or in the motor cylinder itself to position *b*, or $p_0$, $l_0$, and $T_0$ absolute.

The *work done on the gas* is

$$\frac{A}{\gamma - 1} k.(T_0 - T_2).$$

Here ignition followed by the addition of H heat units is *supposed* to take place instantaneously at *constant volume*, and

FIG. 197.



the pressure rises to the highest point $c$, which we imagine $p$, $l$, and T. The mixture expands along the adiabatic $c\,d\,d'$ doing work on the piston to the atmospheric line of pressure, and the temperature has fallen to $T_1$ (say). The work done by the gases in this operation is

$$\frac{A}{\gamma - 1} k.(T - T_0).$$

In the return stroke of the piston, the burnt products with heat $h$ are rejected at constant pressure along the atmospheric line.

The shaded area represents the available or effective work done by the gases being the difference between the pump and motor cylinder diagrams.

The efficiency in this imaginary case is easily obtained by settling the heat account.

Total heat supplied at constant volume: $H = C_v(T - T_0)$.

Total heat rejected at constant pressure: $h = C_p(T_1 - T_2)$.

So that, heat utilised is the difference: $H - h$.

Hence, we find the efficiency

$$\frac{H - h}{H} = \frac{C_v(T - T_0) - C_p(T_1 - T_2)}{C_v(T - T_0)}.$$

$$\therefore \text{ Efficiency} = 1 - \gamma\frac{T_1 - T_2}{T - T_0} \; . \; . \; . \; . \; . \quad (4)$$

And $T_1$ is known, since

$$\frac{T}{T_0} = \left(\frac{T_1}{T_2}\right)^{\gamma}, \text{ or } \frac{T_1}{T_2} = \left(\frac{T}{T_0}\right)^{\frac{1}{\gamma}}.$$

This is the ideal aimed at in compression engines, but we have not a case of expansion to atmospheric pressure.

The **most common case** in practice is where the charge after ignition is allowed to expand to its original volume before compression. The imaginary indicator diagram for such a cycle is *a b c d a*. Always suppose $T_1$ to be the absolute temperature after expansion, when the pressure is $p_1$ and volume $l_1$.

It is convenient for variable expansion to express efficiency as the ratio of total work done to the total energy of explosion.

That is

$$\frac{w}{E} = \frac{\frac{A}{\gamma - 1}.k.(T - T_1) - \frac{A}{\gamma - 1}.k.(T_0 - T_2)}{\frac{A}{\gamma - 1}.k.(T - T_0)}$$

$$= \frac{T - T_1 - (T_0 - T_2)}{T - T_0} = \frac{T - T_0 - (T_1 - T_2)}{T - T_0}$$

Therefore

$$\text{Efficiency} = 1 - \frac{T_1 - T_2}{T - T_0} = 1 - \frac{T}{T_0}, \; . \; . \; . \quad (5)$$

$$\frac{T_1}{T} = \frac{T_2}{T_0} = \left(\frac{l_0}{l_2}\right)^{\gamma - 1}.$$

It is evident from equation (5) that the efficiency depends directly on the amount of compression, or rather on the ratio of the temperature of the mixture $T_0$ after compression to that, $T_2$, before it.

Thus if the charge at $T_2 = 300°$ absolute be compressed adiabatically till $T_0 = 500°$ absolute before ignition, the ideal efficiency will be $1 - 0{\cdot}6$ or $0{\cdot}40$.

Greater compression increases the efficiency.

The advantages of compression are at once seen by comparing this type with the early Lenoir.

**Compression before ignition** is also desirable from a mechanical point of view, because as the crank passes the dead point under pressure it takes the impulse from the explosion without sudden shock or vibration, and the parts can be easily balanced.

Greater regularity in driving is obtained by performing the cycle in one revolution, so that there is an explosion and consequently an impulse given to the driving shaft once in every revolution. This is important when driving dynamo machinery for electric lighting purposes. In short, the more uniform and frequent the application of the driving force, the better for regularity of working.

Another important case of this type of engine cycle is that corresponding to the ideal indicator diagram *a b c d d′ e a,* in which the *gases are allowed to expand to double their volume before compression.* The **Atkinson "Cycle" engine** is an example. This engine clearly utilises more of the available heat than one of the previous type.

Let $T_1$ be the absolute temperature of the gases after expansion at $d'$, Fig. 197, with pressure $p_1$ and volume $l_1$ just before the exhaust valve opens to reject the gases with their heat at constant volume.

Suppose at *e* the pressure is atmospheric and the temperature $T_3$.

The heat rejected during the operation $d' e = C_v (T_1 - T_3)$,
and „ „ „ „ $e a = C_p (T_3 - T_2)$.
Hence for this ideal diagram *a b c d' e a*, Fig. 197.

$$\text{Efficiency} = \frac{H - h}{H} = \frac{C_v (T - T_0) - C_v (T_1 - T_3) - C_p (T_3 - T_2)}{C_v (T - T_0)}$$

$$\therefore \text{ Efficiency} = 1 - \frac{(T_1 - T_3) + \gamma (T_3 - T_2)}{T_1 - T_0} \quad . \; . \; (6)$$

By inspection of the ideal diagram, Fig. 197, it is clear that an engine working with this cycle will approximate very closely in practice to the best conditions, since nearly the whole area is included in the diagram of this engine.

The actual diagram, Fig. 198, enables us to compare the real with the ideal. The combustion, instead of being instantaneous as assumed above, continues throughout the expansion, and sustains the pressure notwithstanding the loss of heat by the water-jacket, and that expended in doing work.

FIG. 198.

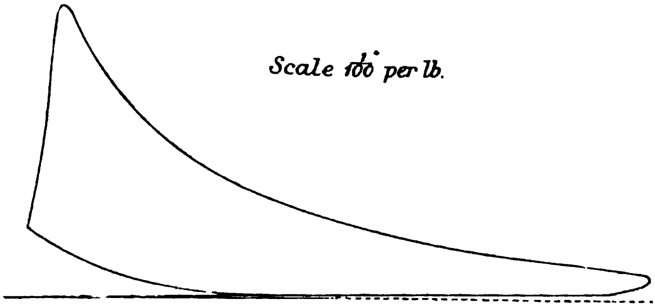


DIAGRAM FROM ATKINSON CYCLE ENGINE.

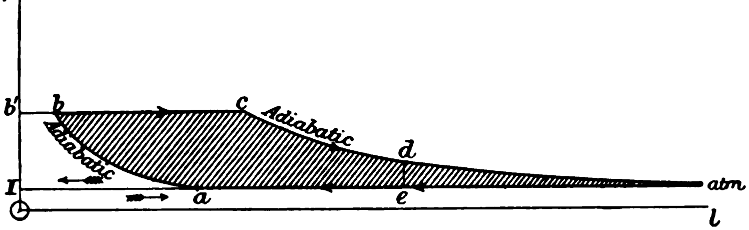
In order to make a fair comparison between indicator diagrams it is advisable to determine the laws of expansion or compression directly from the curves rather than assume true adiabatic expansion indiscriminately for all cases.

## Heat supplied at Constant Pressure.

The ideal diagram of this cycle is shown Fig. 199. The shaded area, representing the available work, is the difference between the motor and pump diagrams.

The mixture of gas and air is taken in during the operation 1 *a*, at atmospheric pressure; it is then compressed along the adiabatic *a b* into a receiver, so that the area 1 *a b b'* is the pump diagram.

FIG. 199.



The compressed mixture is then burned gradually at constant pressure in communication with the motor cylinder, so that H units of heat are supplied at constant pressure along *b' c*. After this, adiabatic expansion is supposed to reduce the gas to atmospheric pressure.

Finally, the gases with *h* units of heat are rejected at constant atmospheric pressure during the return stroke of the piston.

The total heat supplied is $H = C_p (T - T_0)$

" " rejected is $h = C_p (T_1 - T_2)$.

Efficiency

$$\frac{H - h}{H} = \frac{C_p (T - T_0) - C_p (T_1 - T_2)}{C_p (T - T_0)}$$

$$= 1 - \frac{T_1 - T_2}{T - T_0}$$

$$\therefore \text{Efficiency} = 1 - \frac{T_2}{T_0}, \quad \ldots\ldots\ldots\ldots \quad (7)$$

where $T_2$ stands for the temperature before compression, and $T_0$ the temperature of compression before ignition.

Thus the efficiency may be increased by greater compression, and it is independent of the highest temperature T of combustion, as in the Ericsson hot-air engine.

Take the atmospheric temperature

$$T_2 = 17^\circ \text{ C. or } 290^\circ \text{ absolute,}$$

and the compression temperature

$$T_0 = 147^\circ \text{ C. or } 420^\circ \text{ absolute.}$$

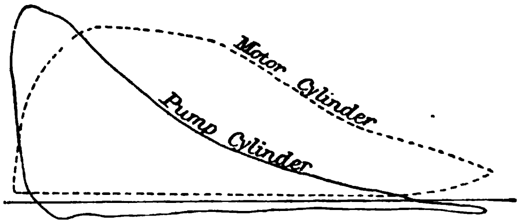
$$\therefore \text{ Ideal efficiency } = 1 - \frac{290}{420} = 0 \cdot 31.$$

In engines of this type, as the Brayton and early Simon, the expansion is not continued to atmospheric pressure, so that the diagram *a b c d e*, Fig. 199 shows the ideal cycle of operations.

The efficiency will evidently be less than that obtained by prolonged expansion, and for any given expansion the ideal efficiency may be deduced from approximate expansion and compression curves.

The actual indicator diagrams, Fig. 200, from the motor and pump cylinders of the early Simon engine are very different from the ideal ones. The compression part is not well marked, and as the compressed mixture of gas and air enters the working cylinder, it is gradually burned, whilst steam generated by the exhaust products is added. This com-

FIG. 200.



INDICATOR CARDS FROM SIMON ENGINE.

because there is considerable fall in temperature and pressur in passing from the one cylinder into the other, and the stean cools the flame. Even in the Brayton, where steam is no used, there is a gradual falling off of temperature to the poin of cut-off. Nor is the expansion curve adiabatic, it is mor nearly isothermal, owing doubtless to the prolonged combustion.

The cycle is a fairly good one, but the engines have complicated mechanism, which makes the cost of manufacture a well as their maintenance, excessive.

## Practical Conclusions.

Theory points to high efficiency with the free piston atmospheric engine, there being high speed of piston. However, the tremendous shock and vibrations, produced when the charge is fired, introduce very serious mechanical difficulties, great structural strength being required even for small powers, and such difficulties practically prevent this type of engine being used for large powers. The noise is also very objectionable in many cases.

The most economical and satisfactory results are to be expected in practice with the cycle of the first type (Class II.), using compression of the charge before ignition and at least one explosion every revolution of the driving shaft for uniformity of speed and working.

Such considerations show that in the internal combustion engine we should seek for

(1) Compression of the charge within certain limits, before ignition.

(2) High speed of piston.

(3) Great expansion of the burnt products.

(4) Application of the regenerator principle to utilise the heat usually rejected with the exhaust gases as well as that carried away by the jacket-water.

# CHAPTER XVII.

## TRIALS OF GAS MOTORS.

INTERNAL combustion engines are tested by a trial run, of many hours duration, and under widely different loads, with a view to determine:

(1) *Practical efficiency and economy* of the motor in turning heat into work, as compared with the performance of an ideal perfect heat engine working between the same limits of temperature; also the actual losses met with in ordinary continuous working.

(2) *Regularity of running and of governing* under steady and suddenly varying loads.

It is of the utmost importance that all the measuring instruments and weights used throughout a trial run should be calibrated and carefully tested, both before and after the experiments.

### Efficiency Tests.

The performance of any heat engine may be stated in a clear and simple form by drawing up a *balance-sheet* of its *heat account.* This idea is due to Hirn. On one side of the heat account we have the total number of heat units supplied to the engine, whilst the different items on the other side show how the engine has disposed of this store of heat energy.

In order to determine the exact **amount of heat given to a gas engine,** the following measurements must be made:—

(*a.*) *Gas consumption.*—The total quantity of gas consumed by the engine is measured by a standard gas meter carefully tested beforehand.

(*b.*) The *temperature and pressure of the gas on entering the* *cylinder* must also be measured, because the volume of a given quantity of gas will be found to vary considerably between the extremes of temperature in winter and summer. These observations may be conveniently made as the gas passes through the meter.

(*c.*) *Analysis and heating power of the gas.*—Samples of the gas are collected during a test, mixed together, and chemical analyses made of the mixture to determine the *average composition* of the gas supplied to the engine during the trial.

From the composition of unit weight of the gas we can calculate the total amount of heat it is capable of giving out when completely burned.

(*d.*) The *quantity of air entering the cylinder* should also be measured by meter, in order to know the *exact ratio of air to gas*, and hence to trace what is going on in the engine cylinder. It is difficult to find a meter of sufficient size to measure all the air required by large engines. However, this might be done by a holder supplied with air from a fan blower through several meters, if necessary.

Messrs. Brooks and Steward, at Hoboken, in America, measured by meter the air for a 6 H.P. Otto engine, the supply being through a fan blower and flexible rubber bags. The latter were placed between the meter and engine, to act as reservoirs, and so prevent the accuracy of the meter being affected by the sudden and intermittent supply taken by the engine.

By means of this arrangement, the effect of varying the supply of gas and air can be investigated and the best proportion of air determined for a given quantity of gas.

(*e.*) The *temperatures of the gases in the cylinder* throughout the cycle of operations. Hitherto these temperatures have been reckoned from the indicator diagrams, as there is no accurate method of determining them by direct measurement. The temperature in the cylinder not only aids in explaining the behaviour of the gases, but also indicates the rate of combustion, that is, the *rate* at which the working fluid actually receives heat during the explosion stroke.

The heating power of the gas having been found by calculation from chemical analysis as well as by direct calorimetric measurement, and the number of explosions in the engine cylinder per minute counted during the trial, we can find the amount of heat that the engine ought to have received per minute.

On the other side of the heat account will be entered:

1. The **quantity of heat turned into work,** as shown by the indicator diagrams, taken at least every quarter of an hour. To work these out we must also know the number of explosions per minute, the diameter of cylinder, travel of piston, and volume of clearance space, including passages and ports in the cylinder filled with gas.

Observations are made at intervals of five minutes, to ascertain

The **actual useful work done on the brake.**

When a simple rope or leather strap friction-brake is used on fly-wheels, we observe the *difference between the pulls* at the ends of the ropes (see page 273), and the number of revolutions per minute as given by a speed counter geared to the crank shaft of the engine.

The difference between the indicated and brake horse-power gives the amount lost in engine friction; whilst the ratio of the brake to the indicated horse-power is called the *efficiency of the mechanism.*

The second item on this side of the heat account is

**2. Heat lost by jacket-water.**

This is determined by the three observations:—

(*a*) *Quantity of water* in lb. per minute passing round the jacket, as measured in gallons by a *water meter.*

(*b*) Temperature of water *entering* the jacket, and

(*c*) „ „ *leaving* „ „ .

**3. The heat carried off by exhaust gases** cannot be found with the same degree of certainty. This is evident because we have to estimate—

(*d*) *Temperature of the gases discharged* from the cylinder.

A pyrometer placed in the exhaust-pipe as near the cylinder temperature of the gases in that pipe during a short interval of time, and such indications must necessarily be below the highest temperature of the gases leaving the cylinder.

The temperature of the gases *before leaving* the cylinder may be arrived at by calculation from the indicator diagrams. The amount of heat found by taking this temperature is too high, and liable to lead to error, because it includes part of the heat in item (2) given to the jacket-water while the hot gases are being driven out of the cylinder into the exhaust-pipe.

(*e*) *Specific heat of the mixture of waste gases.*—The specific heats of the burnt products are calculated from the specific heats of the constituent gases, on the assumption of complete combustion.

(*f*) *Weight of the escaping products of production* is also obtained from that of the charge of gas and air in the cylinder.

**4. Balance of heat supplied.**—There is always some heat lost by convection and radiation from the engine. This item should be comparatively small.

Now, when we add together the heat turned into work and carried off by the jacket-water and exhaust-gases, the amount ought to be equal to the heat received. If not, the balance of the heat account, that is, the heat unaccounted for, may never have been received by the working charge, because of incomplete combustion. This may be shown by the heat reception curve.

From the above data it is an easy matter to work out the gas consumption per hour in cubic feet per brake and per indicated horse-power.

The cost of maintenance will include the cost of fuel consumed, oil used for lubrication, attendance, depreciation, and repairs of working parts, together with interest on the amount of capital invested.

Knowing the volume of the clearance space in the motor cylinder, and the results of the above observations, we can gain useful information about the behaviour of the working fluid throughout a complete cycle of operations, by *further study of the indicator diagrams.*

In the first place, if we neglect the small contraction due to the combustion of the charge, and assume that the mixture behaves like a perfect gas, starting with a known volume, temperature, and pressure, we can at once calculate the temperature at any point until the exhaust opens, by taking the pressure and volume from the diagram.

Again, from actual measurements of the pressures on a number of indicator cards, we may construct an ideal mean diagram, in which the compression and expansion curves are represented by equations of the form $p\, l^m$ = constant.

From this we can determine the quantity of heat that the fluid shows it receives per inch travel of the piston, as well as the work done *by* and *on* it during the separate operations. Then the efficiency of an ideal heat-engine, having the cycle of operations shown in this mean diagram, may serve as a check on the results obtained from the actual engine, whilst both of these fall far short of the efficiency of a perfect heat-engine working between the same temperatures.

In estimating the relative **cost of power** by a gas engine driven with cheap gas from a Dowson producer, and by a steam engine with boiler, the simple and direct way is to take in each case the weight of fuel (coal) used per hour per horse-power, as it is no more necessary to determine the volume of gas consumed in the gas engine than to know the volume of steam used in the steam engine. All such arrangements aim at converting as large a fraction as possible of the total heat-energy in the coal, oil, or other fuel, into mechanical energy.

## Regularity of Working.

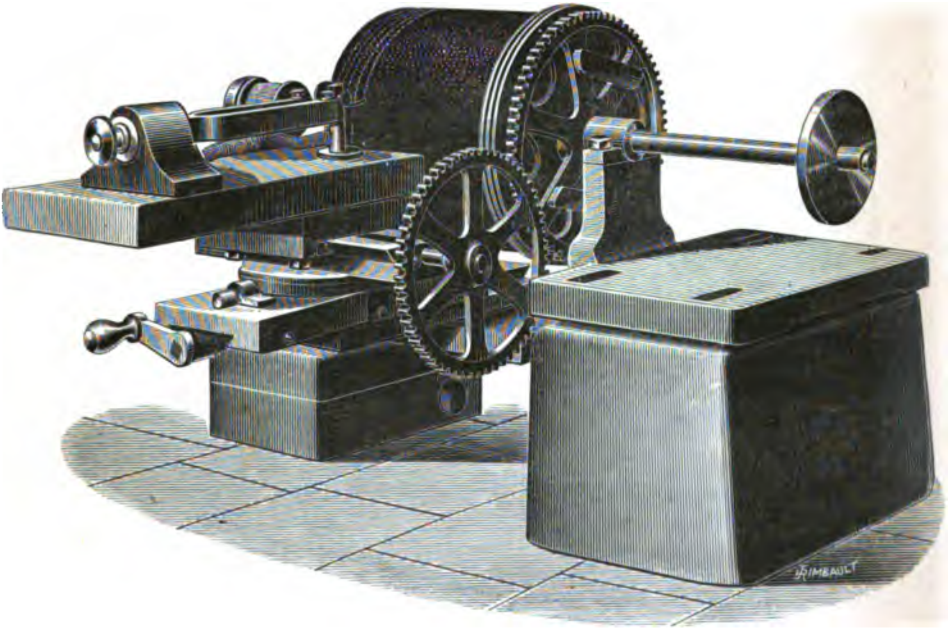
For many purposes, such as electric lighting, it is of primary importance to have the power developed uniformly.

Any variation in the speed of rotation of the crank shaft during each revolution may be measured and recorded by

(*a*) Some such **speed indicator** as that shown in Fig. 201.

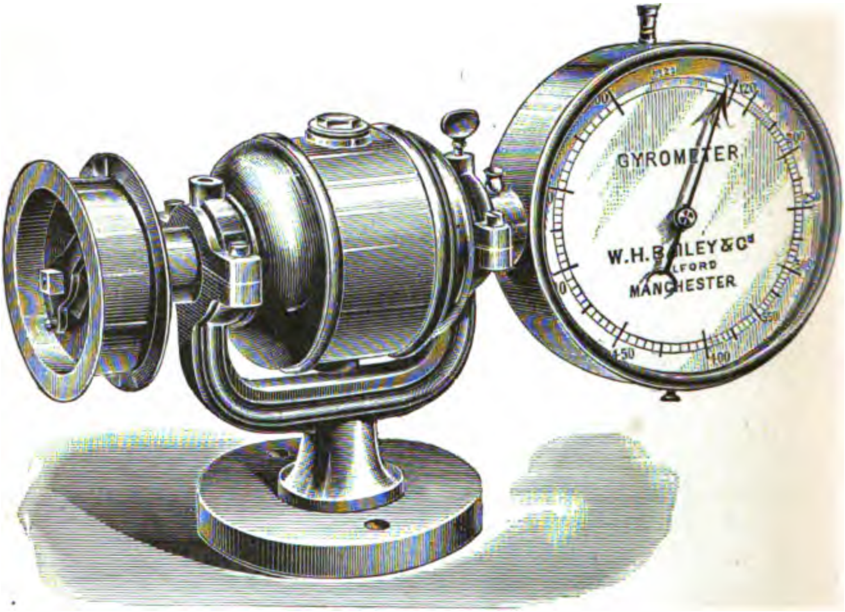
It consists of a drum covered with prepared paper, and rigidly coupled to the shaft whose speed is required. As the drum revolves with the shaft, a wavy line is traced on this paper by a metal style carried on one limb of a tuning-fork, which is kept in vibration by an electric current, and gives a known definite number of vibrations per second. Therefore, the number of waves traced by the style records the time taken by the shaft in turning through any portion of a complete revolution. The tuning-fork is mounted on a slide-rest, which is moved by a screw parallel to the axis of the drum, and in this way a continuous register is obtained of every slight variation in the speed.

FIG. 201.



(*b*) A *gyrometer*, *tachometer*, or *speed indicator* is intended to give, at every instant, the speed of a shaft in revolutions per minute. This indicator is usually provided with a pulley, and may be driven in either direction from the shaft by a smooth and pliable belt, carefully jointed. The actual speed of shaft is then calculated from the ratio of the diameter of the driving pulley to that on the indicator.

FIG. 202.



Such an instrument may also be fixed or coupled to a shaft, and then records the speed of shaft directly.

(*c*) The *average speed* of a motor may be taken for any minute, half-minute, or shorter interval, by an ordinary *counter*, which records the total number of revolutions during that measured interval of time. There are also *stop* devices, which give the number of revolutions during any required interval, as a half-minute.

(*d*) In the case of an engine driving a dynamo-machine which supplies current *directly* to incandescent lamps, a very good test of regularity in the speed of dynamo is afforded by the brightness and steadiness of the lamps. Any *pulsation or* *twinkling* of the lamps tells of variation in speed of dynamo, due either to *slipping of driving belt or irregularity of engine speed*, provided the dynamo-machine is always perfectly self-regulating.

This combination also furnishes us with a *severe test of the sensibility of the governor*, when part of the load of lamps is suddenly thrown off by means of a switch, thereby varying the strength of electric current taken from the dynamo, whilst the supply should be kept at constant potential. *Hunting* of the governor is detected by *flickering* or *variations in the brightness* of the lamps.

## RESULTS OF TRIALS.

### Otto Engine.

Some very complete experiments were made upon an Otto Gas Engine by Messrs. Morgan Brooks and J. E. Steward, under the direction of Professor Robert H. Thurston, at the Stevens Institute of Technology, Hoboken, in America, during the months of May and June, 1883.

The engine was a 6 H.P. nominal, diameter of cylinder 8·5 inches, and stroke 14 inches.

The volume of the clearance space or compression chamber was determined by weighing the water required to fill it. The clearance space was thus found to be 38 per cent. of the total cylinder volume.

Observations for the different measurements were usually made at intervals of five minutes, and sometimes oftener.

*Meters* were used to measure both the *gas and air* entering the cylinder, with flexible rubber bags in the supply pipe between the meters and engine. The ratio of air to gas was found to be about 7 to 1, when the engine was working most economically at full power. The temperature of the gas supplied was 24° C. Now, since, at constant pressure, the volume of the same weight of a perfect gas varies directly as its absolute temperature, it follows that one cubic foot of gas at 24° C. becomes

$$\frac{273}{273 + 24} = 0 \cdot 92 \text{ cubic feet at } 0^\circ \text{ C.}$$

For the purpose of comparison, the cubic feet of gas indicated on the meter should, therefore, be reduced in this ratio. On the other hand, the figures given below for gas consumption do not include that used for ignition, which amounts in all to about 7 cubic feet of gas per hour, or less than 1 cubic foot per hour per brake H.P.

The quantity of the jacket-water was measured by meter, and its temperature, before entering and immediately after leaving the jacket, was observed by standard thermometers. The water was heated from the mean temperature 22° C., to 48° C. in the lowest full-power experiment and up to 89·4° C.

A *Bulkley pyrometer*, placed in the exhaust pipe as near as possible to the cylinder, gave the average temperature to which it was heated by the discharged gases, between 299° C. and 432° C.

A *counter* attached to a link moving the slide valve, gave the total number of double revolutions.

A *Tabor indicator* was used to take the indicator cards, and their areas were measured with an *Amsler planimeter*. The area between the exhaust and admission lines, represents the work done in expelling the burnt products and drawing in the fresh charge. On this account a reduction of $\frac{1}{10}$th atmosphere is made in the mean effective pressure taken from the cards in the ordinary way.

The *useful work* of the engine was measured by a *Prony brake*, made of two iron hoops, with blocks of wood fastened to them, and clamped round a brake pulley 30 inches in diameter, keyed on the crank shaft of the engine. The difference between the indicated and useful work is the amount wasted in friction of the engine. In all the tests at full power, the average friction of the engine was 18·6 per cent.

In one experiment at full power the speed was 158 revolutions per minute, the temperature of the water leaving the jacket 49° C., and that of the exhaust gases 430° C.; the results obtained were :—

| Indicated H.P. | Brake H.P. | Gas used per Hour in Cubic Feet. | | Efficiency of Mechanism per Cent. |
|---|---|---|---|---|
| | | Per Ind. H.P. | Per Brake H.P. | |
| 9·6 | 8·1 | 24·5 | 29·1 | 84·3 |

Reduced to 0° C., this gas consumption per hour is 22·5 cubic feet and 26·8 cubic feet per indicated and per brake H.P. respectively. The gas used was of poor quality, its heat value being only 617·5 thermal units (lb. degree Fahr.), or 476,710 ft. lb. per cubic foot.

One cubic metre of the gas used weighs 0·606 kilograms, and the total heat of combustion of one charge, 0·0014 cubic metre or 0·001867 lb., is 7·69 calories. This amount of heat is disposed of by the engine as follows :—

| DISTRIBUTION OF HEAT. | Heat Units per Explosion. | Percentage of Heat of Combustion. |
|---|---|---|
| Heat turned into work indicated in cylinder, including useful work and friction .. .. .. | 1·33 | 17·0 |
| Lost in hot exhaust gases .. .. .. .. .. .. | 1·18 | 15·5 |
| Given to jacket-water .. .. .. .. .. .. .. | 4·00 | 52·0 |
| Lost by radiation, convection, &c. .. .. .. .. | 1·18 | 15·5 |
| | 7·69 | 100·0 |

The amount lost by radiation is usually not so great as these figures indicate. Professor Thurston estimated this loss in a 7 H.P. about 10·76 per cent., whilst the exhaust gases carried off 23·55 per cent., and the jacket-water 46·9 per cent. of the total heat of combustion.

The *temperatures* throughout the cycle were calculated from the indicator card on the assumption that the mixture obeys the law, $\frac{pv}{T} =$ constant. The mixture after admission was at 120° C., when compressed before ignition 249° C., after explosion 1657° C., and before exhaust valve opens 1159° C.

Since the equation to the curves on the indicator card is of the form

$$p\, v^m = constant,$$

where $m = 1 \cdot 37$ for an adiabatic curve;
measurements of the pressures and volumes on the cards give

for the compression curve, $m = 1 \cdot 335$
and „ expansion „ $m = 1 \cdot 363$.

This shows that during compression of the gaseous mixture before ignition, 0·05 calorie of heat was rejected by the gases and absorbed by the cooling water, so keeping the compression curve below the adiabatic.

Again, since the expansion curve is nearly adiabatic, it is clear that, after ignition and explosion proper, the expanding gases must be continuously receiving heat nearly equal in amount and at the same rate as they are giving out heat to the cooling jacket-water, in order to keep up the pressure at the same time. This heating during expansion can only come from the prolonged combustion of the gases throughout the stroke. The amount of heat given by the gases to the cooling water during expansion cannot be accurately estimated from the indicator cards, because a considerable quantity is given up to the jacket-water after the exhaust valve opens and while the hot gases are being driven out of the cylinder. Of this amount we can only get a vague idea from the card by the temperature before exhaust, estimated on the assumption that the burning mixture behaves like a perfect gas which receives heat from an outside source.

It is a simple matter to measure the total heat absorbed by the cooling water, but we cannot, with the same degree of accuracy, determine the exact quantity of heat given out by the gases during expansion, because of our uncertainty as to the heat actually received by these gases; seeing that, in many cases, combustion goes on during the whole expansion, though doubtless not so rapidly towards the end as at the beginning of the stroke.

Taking the total heat received along the explosion and expansion curves on the indicator card as the thermal equivalent of the work area bounded by these curves and indefinitely extended adiabatics through their extremities (see page 476), the indicated heat per explosion only comes to 4·67 calories. But during compression 0·05 calorie was rejected; leaving the total heat received 4·62 calories. Now the total calculated heat of combustion of one charge is 7·69 calories, so that 3·07 calories, or 40 per cent. of the total heat, is left unaccounted for by the indicator card.

This discrepancy is attributed to dissociation, which prevents the complete combustion of the gas, with evolution of the total heat, taking place instantaneously, but allows further burning, as the temperature falls, even until after the exhaust valve opens.

## Atkinson's Cycle Engine.

A trial of the *first "Cycle" engine* ever constructed was made by Professor W. Cawthorne Unwin, F.R.S., on the 4th April, 1887.

The engine was a 4 H.P. nominal, diameter of cylinder 7·5 inches, with working stroke of 9·25 inches.

Indicator diagrams were taken every 5 minutes, and simultaneously observations were made of the load on the brake, speed counter, weight and temperature of the jacket-water, and the gas consumption.

A *Crosby indicator* was used, with a spring of strength 100 lb. to the inch. The diagram, Fig. 203, has a peculiar wave in the exhaust line, probably due either to backlash in the instrument or to vibration of the exhaust valve.

The *friction brake* was a leather strap over half of the fly-wheel, with the weights at one end and a spring balance at the other. This spring balance gave the slight pull necessary to put friction on the brake.

In the first trial at normal full power the following figures were obtained:—

| Indicated H.P. | Brake H.P. | Gas used per Hour in Cubic Feet. | | Efficiency of Mechanism per Cent. |
|---|---|---|---|---|
| | | Per Ind. H.P. | Per Brake H.P. | |
| 5·563 | 4·889 | 19·78 | 22·50 | 87·9 |

The gas consumption was at the rate of 1·834 cubic feet per minute. Reckoning the heat value at 628·7 thermal units (lb. degree Fahr.) per cubic foot, the gas furnished 890,000 ft. lb. of heat energy to the engine per minute. This amount of heat was disposed of by the engine as follows:—

| DISTRIBUTION OF HEAT. | Foot-pounds per Minute. | Percentage of Heat of Combustion. |
|---|---|---|
| On brake, 4·889 H.P., or .. .. .. .. .. | 161,337 | 18·12 |
| Engine friction, 0·674 H.P., or .. .. .. .. | 22,242 | 2·50 |
| Accounted for on indicator diagram .. .. .. | 183,579 | 20·62 |
| Given to jacket-water, 2·09 × 106·9 × 772 .. | 172,500 | 19·37 |
| Leaving for exhaust gases, radiation, &c. .. .. | 533,921 | 60·00 |

A good average indicator diagram, taken during this trial, is shown in Fig. 203; the dotted lines being a diagram from a 4 H.P. Otto engine, as given in Dr. Slaby's Report.*

For the sake of comparison, these diagrams are plotted with the same compression stroke. Clearly the expansion is much greater in the Atkinson engine than in the Otto.

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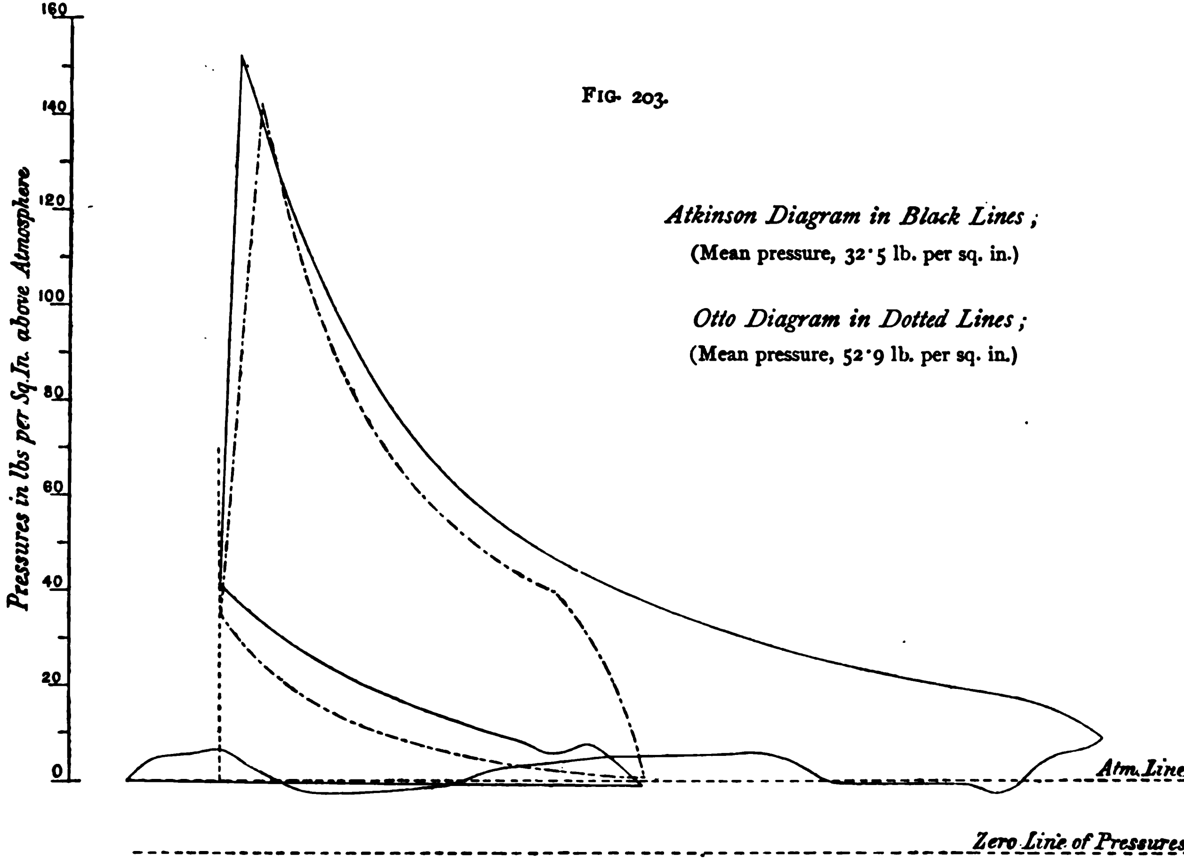
* Appendix to paper on *Gas and Caloric Engines*, by Professor Fleeming Jenkin, *Proceedings Inst. C.E.*, 1885.

FIG. 203.



(Signed) W.C. UNWIN.

Since the equations to the curves are of the form

$$p\,v^m = \text{constant},$$

where $m = 1\cdot375$ for an adiabatic curve;
measurements of the pressures and volumes on the Cycle diagram, give

$$\text{for the compression curve, } m = 1\cdot399$$
$$\text{and} \quad ,, \quad \text{expansion} \quad ,, \quad m = 1\cdot305$$

The compression curve is thus a little steeper that the adiabatic, showing that the gaseous charge gains heat from the cylinder walls during compression before ignition.

The expansion curve lies between an adiabatic and isothermal, so that more heat is developed by gradual combustion going on throughout this stroke than is given to the jacket-water.

On the other hand, the expansion curve on the Otto diagram is nearly adiabatic, the gain and loss of heat being equal, so that the combustion was completed earlier and not so marked during the whole expansion.

### Griffin Double-acting Engine.

The Griffin double-acting gas engine, as described above, page 193, was tested at the Britannia Engineering Works, Kilmarnock, by Professor Alex. B. W. Kennedy, F.R.S., on the 4th February, 1888.

The engine was of 8 H.P. nominal, with diameter of cylinder 9 inches, and length of stroke 14 inches.

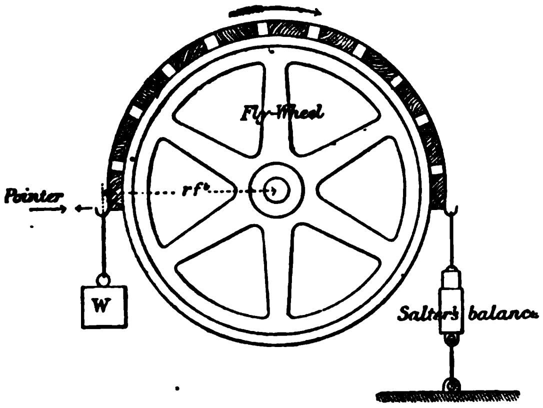
In these experiments the four principal quantities measured were the *indicated and brake horse-power*, *gas consumption*, and *quantity of heat rejected in the jacket-water.*

Observations were taken every five minutes; and the two full-power experiments, with an interval of 10 minutes between them to change the conditions of working, formed practically one continuous run of four hours.

each end of the cylinder. In order to ascertain with greater precision the indicated work spent in driving out the hot gases and drawing in the next charge, several sets of indicator cards were taken with $\frac{1}{10}$ springs. With these weak springs ferrules were fixed on the piston-rods of the indicators to prevent injury. It was found that the work done in these two strokes meant a reduction of 3·54 lb. per square inch in the mean pressure during the working stroke as calculated in the ordinary way from the indicator card.

The friction brake consisted of straps fitted with wooden blocks over each fly-wheel, the weight and spring-balance being attached as shown in Fig. 204. These brakes worked well with only a little tallow as lubricant.

FIG. 204.



FRICTION BRAKE.

The quantities of *gas* and *water* used were measured by meters fed from the mains, and the temperatures observed every 5 minutes.

The following are the results of the full-power trial throughout the total run of four hours :—

| Indicated H.P. | Brake H.P. | Gas used per Hour in Cubic Feet. | | Efficiency of Mechanism per Cent. |
|---|---|---|---|---|
| | | Per Ind. H.P. | Per Brake H.P. | |
| 17·46 | 14·94 | 18·92 | 23·58 | 85·6 |

The gas was of excellent quality, its calculated heat value being 677 thermal units (lb. degree Fahr.), or 522,644 ft. lb. of heat energy per cubic foot. The gas was consumed at the rate of 0·03946 cubic foot, or 0·001283 lb. per explosion, which furnished 26·7 thermal units, or 20,620 ft. lb. of energy. Of this total amount of heat it will be seen by the heat account that the engine turns into work 20 per cent., the jacket-water carrying off 37·6 per cent., whilst about 42 per cent. is rejected with the hot exhaust gases and the scavenger or blank charge.

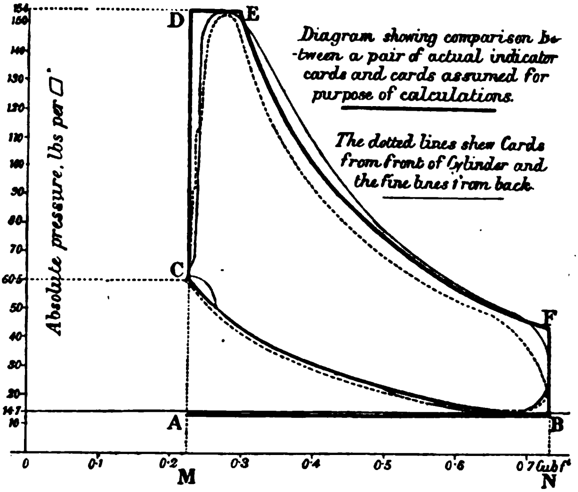
HEAT ACCOUNT.

*Dr.* *Cr.*

| | Foot-pounds. | | Foot-pounds. |
|---|---|---|---|
| Total heat due to the complete combustion of 0·001283 lb. of gas | 20,620 | Heat turned into work .. .. | 4,130 |
| | | Heat rejected in jacket water | 7,740 |
| | | Do. scavenger charge | 240 |
| | | Do. exhaust .. .. | 8,440 |
| | | Heat unaccounted for .. .. | 70 |
| | 20,620 | | 20,620 |

Some of the indicator diagrams taken during the trial are given above, in Chapter VI.

Many measurements of the indicator cards were made to construct the actual mean card of the engine. The point E, Fig. 205, on this ideal card is the mean position of the point of intersection of the expansion line and initial pressure line. The combustion is supposed to take place mainly at constant volume along C D.



GRIFFIN IDEAL INDICATOR DIAGRAM.

The mean values of pressure and volume used for the principal points, together with the calculated temperatures, are as follow :—

| Points. | Pressure (lb. per square inch) Absolute. | Volume (Cubic Feet). | Temperature (Fahrenheit). |
|---|---|---|---|
| A | 13·7 | 0·225 | 110° |
| B | 13·7 | 0·730 | 110° |
| C | 60·5 | 0·225 | 324° |
| D | 154·0 | 0·225 | 1535° |
| E | 154·0 | 0·295 | 2155° |
| F | 44·4 | 0·730 | 1395° |

In the equation to the curves,

$$p\, v^m = constant,$$

$m = 1·384$ for an adiabatic expansion curve, since 1·384 is the ratio between the specific heats of the products after complete combustion.

Measurements of the pressures and volumes from the cards give

for the actual mean compression curve, $m = 1\cdot262$,
and „ „ „ expansion „ $m = 1\cdot373$.

Thus the compression curve is not so steep as the adiabatic; in other words, part of the heat produced during compression is rejected to the jacket-water.

The expansion curve lies very close to the adiabatic, so that heat must be received by combustion throughout this stroke, to make up for the loss to the jacket-water.

## Atkinson, Crossley, and Griffin.

The Society of Arts appointed three judges: Dr. John Hopkinson, F.R.S., Professor Alex. B. W. Kennedy, F.R.S., and Mr. Beauchamp Tower, to make trials of motors for electric lighting. These trials were carried out at South Kensington during September 1888.

Three gas engines were sent for competition.

The *Crossley engine* was a 9 H.P. nominal, having a single cylinder 9·5 inches in diameter and 18 inches stroke. The charge was ignited by a heated tube, the time of ignition in the cylinder being controlled by a valve actuated by a lever as described in Chapter VII. The dynamo was driven directly from a high-speed counter shaft with fly-wheel upon it, and running in bearings attached to the engine bed. The fly-wheel was 65·5 inches diameter, 9 inches broad on face, and weighed 1,652 lb.

The *Griffin engine* was of 8 H.P. nominal, with cylinder 9·02 inches in diameter and 14 inches stroke. This double-acting engine, of the type described in Chapter VI., had two fly-wheels, each 60·1 inches diameter by 7·5 inches broad on face, and each weighed 1,144 lb.

The *Atkinson "Cycle" engine* was of 6 H.P. nominal, with cylinder 9·5 inches in diameter, the suction stroke 6·33 inches, the compression stroke 5·03 inches, the working stroke 11·13 inches, and the exhaust stroke 12·43 inches.

This engine (page 49) had a fly-wheel on each end of the crank shaft, and each fly-wheel was 69·3 inches diameter by 4·5 inches broad on face, and weighed 1462 lb.

These three engines were tested, during (1) a continuous run of 6 hours at full power, (2) a 3 hours' run at half power, and (3) a trial with the engine running light.

The *quantity of gas consumed* in the engine itself and that used for the ignition were separately measured, readings being taken every quarter of an hour, on Wright's standard wet-meters. Its pressure and temperature were also observed in the meter. Samples of the gas were also taken at frequent intervals during each trial, the mixture being afterwards analysed and its heat value determined.

*Indicator diagrams* were taken at intervals of a quarter of an hour, and the indicator springs afterwards tested. Diagrams were also taken with light springs, to find the work done during "pumping strokes" in driving out the hot gases and drawing in the charge.

The *friction-brake* used was of the simplest kind (Fig. 162, page 271). A pair of ropes, kept apart by transverse pieces of wood, and making one turn round the fly-wheel, had the dead load applied by weights, whilst a spring balance pulled at the other end of the ropes to put on friction. Readings were taken every five minutes.

The *number of revolutions* of each engine were given by a counter read every quarter of an hour, and the *number of explosions* found by deducting the actual number of misses, which were separately counted.

In the **Speed Trials** the indicator Fig. 201 was used, to record variation in speed when the load was thrown off, as well as the cyclical variations.

The *quantity of water* cooling the cylinder was measured by a Schönheyder water-meter, and its *temperature* on leaving the jacket observed by means of a thermometer.

The weight of oil used for cylinder lubrication during the run was noted, and its value per hour per indicated H.P. expressed in cubic feet of gas costing 2*s.* 6*d.* per 1000 cubic feet.

Tests were also made to ascertain the

## Regularity of Running and of Governing.

The engines were employed to drive a dynamo machine, and the electric current from the machine was taken through a metallic resistance which could be varied at will by switches, whilst the brightness of an incandescent lamp connected to the dynamo showed any variation in speed when the whole load was suddenly thrown off.

| Measurements. | Atkinson. | Crossley. | Griffin. |
|---|---|---|---|
| | Sept. 21, 1888. | Sept. 19, 1888. | Sept. 27, 1888. |
| Revolutions per minute | 131·1 | 160·1 | 198·1 |
| Explosions ,, ,, | 121·6 | 78·4 | 129·0 |
| Percentage variation in speed with full load and light | 1·75 | 6·57 | 2·2 |
| Mean initial pressure | 166·0 | 196·9 | 132·3 |
| Mean effective pressure | 46·07 | 67·9 | 54·15 |
| Indicated H.P. | 11·15 | 17·12 | 15·47 |
| Brake load, nett | 130·5 | 177·4 | 130·7 |
| Brake H.P. | 9·48 | 14·74 | 12·51 |
| Mechanical efficiency | 0·85 | 0·86 | 0·81 |
| Gas per hour, main | 209·8 | 351·8 | 350·2 |
| ,, ,, ignition | 4·5 | 3·5 | 7·1 |
| ,, ,, total | 214·3 | 355·3 | 357·3 |
| Gas per indicated H.P. per hour, total | 19·22 | 20·76 | 23·10 |
| ,, ,, brake ,, ,, ,, | 22·61 | 24·10 | 28·56 |
| Gas equal to cylinder oil used per indicated H.P. per hour | 1·59 | 1·54 | 2·72 |
| Heat value of gas in (lb. degree Fahr.) thermal units per cubic foot | 633 | 626 | 624 |
| Cooling water per hour | 680 lb. | 713 lb. | 1022 lb. |
| Rise of temperature | 50° F. | 128° F. | 71·8° F. |
| H.P. spent in driving engine | 1·67 | 2·38 | 2·96 |
| Mean pressure during working stroke, equivalent to work done in pumping strokes | 1·0 | 2·19 | 2·40 |
| Corresponding indicated H.P. | 0·26 | 0·55 | 0·69 |

The principal results of the full-power trials, each of five hours' duration, are given in the preceding table.

In order to compare the performance of the different engines, a heat account is worked out and an ideal indicator diagram, Figs. 207, 209, and 211, for each engine constructed from the mean of the actual pressures measured on all the indicator cards, such as shown in Figs. 206, 208, and 210 respectively.

FIG. 206.

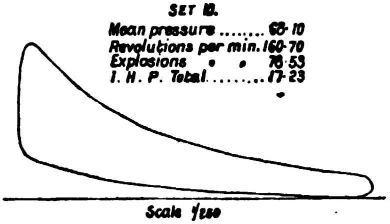


FIG. 208.

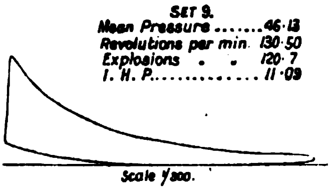
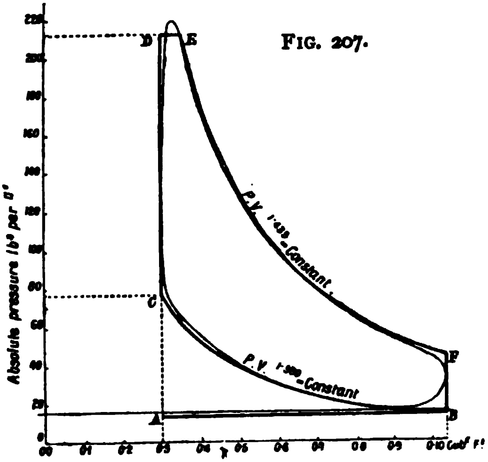
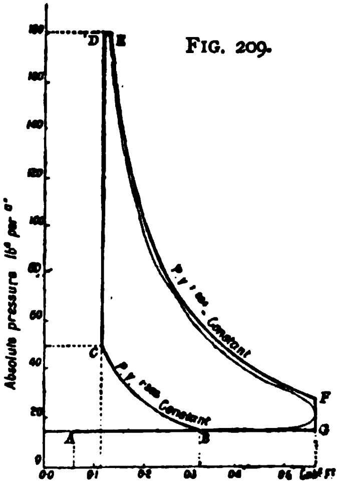


FIG. 207.



CROSSLEY ENGINE.

FIG. 209.



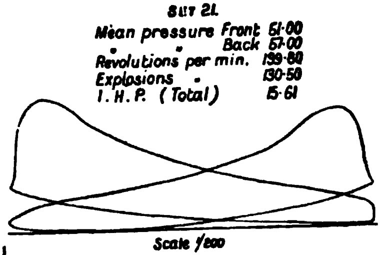
ATKINSON ENGINE.

For instance, the point D is plotted from the mean height of all the indicator cards, then the average distance, D E, is laid off, and the other points are found as already explained, p. 526.

The temperatures at the different points of the cycle are calculated on the assumption that the temperature of the charge after it has been drawn into the cylinder is the same as the highest temperature of the water leaving the jacket. From this the mean values of the principal points on the ideal indicator diagram, Fig. 209, of the Atkinson engine are :—

| Points. | Pressure (lb. per square inch) Absolute. | Volume in Cubic Feet. | Temperature (Fahrenheit). |
|---|---|---|---|
| A | 14·87 | 0·064 | 116° |
| B | 14·87 | 0·324 | 116° |
| C | 50·30 | 0·118 | 259° |
| D | 180·90 | 0·118 | 2160° |
| E | 180·90 | 0·135 | 2530° |
| F | 29·00 | 0·575 | 1560° |
| G | 14·87 | 0·575 | — |

FIG. 210.



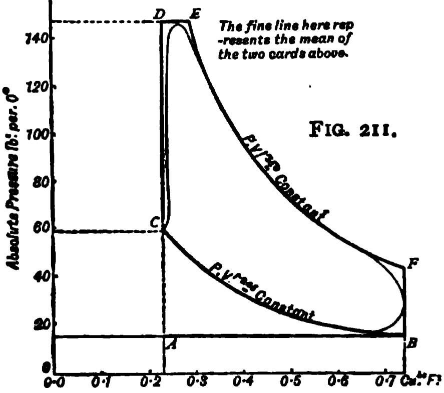


FIG. 211.

GRIFFIN ENGINE.

### GAS USED IN ATKINSON ENGINE.

*September 21st*, 1888.

| Constituents. | Proportion by Volume. | Weight of 1 Cubic Foot. | Weight in 1 Cubic Foot of Gas. | Proportion by Weight. | Heat Value per lb. down to 100° C. (lb. degree F.) | Heat Value per lb. of Gas, down to 100° C. (lb. degree F.) | Weight of Oxygen required to burn 1 lb. of Gas. | Weights of Products of Complete Combustio for 1 lb. Gas. | |
|---|---|---|---|---|---|---|---|---|---|
| | | At Standard Pressure and Temperature. | | | | | | Steam. | Carbonic Acid. |
| | per cent. | lb. | lb. | | heat units | heat units | lb. | lb. | lb. |
| $CH_4$ .. .. | 37·73 | 0·0447 | 0·01680 | 0·511 | 21,510 | 10,991 | 2·044 | 1·150 | 1·405 |
| $C_2H_4$, &c. .. | 4·07 | 0·1410 | 0·00574 | 0·174 | 20,100 | 3,497 | 0·597 | 0·224 | 0·547 |
| H .. .. | 48·56 | 0·00559 | 0·00271 | 0·082 | 52,200 | 4,280 | 0·656 | 0·738 | .. |
| CO .. .. | 4·19 | 0·0783 | 0·00328 | 0·099 | 4,350 | 431 | 0·057 | .. | 0·156 |
| N .. .. | 4·93 | 0·0783 | 0·00386 | 0·117 | .. | .. | .. | .. | .. |
| $CO_2$ and O | 0·52 | 0·1060 | 0·00055 | 0·017 | .. | .. | .. | .. | .. |
| | 100·00 | | 0·03300 | 1·000 | | 19,199 | 3·354 | 2·112 | 2·108 |

Mean ideal cards, Figs. 207 and 211, have been worked out in the same way for the other engines. The highest limit of temperature for the burning gases is reckoned to be 3000° Fahr. in the Crossley, and only 2120° Fahr. in the Griffin engine.

The gas used varied in quality from day to day, hence it became necessary to have careful analyses made of the samples taken during each trial, in order to calculate and determine experimentally the heating value of the gas supplied to the different engines.

From this we see that 1 cubic foot of the coal gas gives out when completely burned 0·033 × 19,199 = 633 heat units, that is, 633 × 772 = 488,676 ft. lb. of heat energy. The heat values thus worked out for the gases used in the Crossley and Griffin engines are 626 and 624 thermal units respectively.

The specific heat of the charge and of the products, when completely burned in the Atkinson engine, are worked out by the judges in their report :—

SPECIFIC HEATS.

| Constituent. | Weight for 1 lb. Gas admitted. | Proportions by Weight in 1 lb. discharged. | Mechanical Equivalent of the Heat necessary to raise the Temperature 1 degree Fahr. of | | | |
|---|---|---|---|---|---|---|
| | | | 1 lb. (Specific Heat). | | Quantity in 1 lb. discharged. | |
| | | | $C_v$ | $C_p$ | $C_v$ | $C_p$ |
| Steam .. | 2·112 | 0·089 | 286 | 371 | 25·4 | 33·0 |
| $CO_2$ .. | 2·125 | 0·089 | 132 | 167 | 11·7 | 14·9 |
| N .. .. | 11·217 | 0·471 | 134 | 188 | 63·1 | 88·5 |
| Air.. .. | 8·346 | 0·351 | 130 | 183 | 45·6 | 64·2 |
| | 23·800 | 1·000 | | | 145·8 | 200·6 |

Hence the ratio of the specific heats of the products is $\frac{200 \cdot 6}{145 \cdot 8} = 1 \cdot 376$; whilst that of the charge is taken the same as for air, *i. e.* 1·408.

has the index $m$ = 1·205, showing that this curve is not so steep as the adiabatic, and the heat rejected to the jacket water is equivalent to 412 ft. lb. For the expansion curve, $m$ = 1·264. The ideal diagram gives 3390 ft. lb. of work per explosion, whilst the mean value of the actual indicated work is 3030 ft. lb., as near an agreement as could well be expected, and the slight discrepancy is seen by inspection of the cards, Fig. 209.

When working at full power during this trial, the gas engines disposed of the total heat of combustion of the gas as follows:—

| Distribution of Heat. | Atkinson Engine. | Crossley Engine. | Griffin Engine. |
|---|---|---|---|
| | per cent. | per cent. | per cent. |
| Heat turned into work, shown on actual indicator diagram .. .. .. .. .. | 22·8 | 21·2 | 19·2 |
| Heat given to jacket-water .. .. .. .. | 27·0 | 43·2 | 35·2 |
| Leaving for exhaust, imperfect combustion, &c., heat unaccounted for .. .. | 50·2 | 35·6 | 45·6 |
| | 100·0 | 100·0 | 100·0 |

---

[*] The student will find further detailed accounts of gas engine tests, with figures obtained and methods of calculation, in:—*Report of the Judges*, Society of Arts' Trials of Motors for Electric Lighting, 1888–89; *Some Experiments upon the Otto Gas Engine*, by Messrs. Morgan Brooks and J. E. Steward, Stevens Institute of Technology, 1883, given in *Van Nostrand's Engineering Magazine*, February 1884; *Comparison of the Lenoir and Otto Gas Motors*, by Dr. A. Slaby, in Appendix to the Paper on *Gas and Caloric Engines*, by Professor Fleeming Jenkin in the series of Lectures on "Heat in its Mechanical Applications," *Proceedings Inst. C.E.*, 1883–84; also *The Gas Engine Indicator-Diagram*, by Professors W. E. Ayrton, F.R.S., and John Perry, D.Sc., F.R.S., in *Philosophical Magazine* for July 1884.

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